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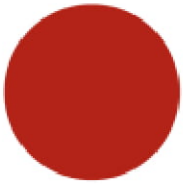
Master's Degree

Mining and Geo-Environmental Engineering

Granulometric inference by image analysis - laboratory tests

José Eduardo Morais

Porto, 2018



Granulometric inference by image analysis – laboratory tests

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This paper marks the end of my academic career, at least for now, the same way it marks the end of a chapter in my life.

I'd like to dedicate this paper to my parents, Maria Leonor Silva and Carlos Silva, who were always present, and moved mountains to make sure I had everything I ever needed. Without them this journey would have been far less pleasant.

I'd also like to thank my aunt, Maria Olinda Morais, uncle, João Monteiro and cousin José Adriano Morais, who were also always there for me, and hopefully will always be.

A special thanks to my advisor, Professor José Soeiro, without whom this paper would be far less interesting, for all the help, input and ideas given.

Lastly, I'd like to thank my friends, especially Ana Leite, for putting up with me during this work, and Cláudia Martins, for all the meals specially prepared and time spent playing "boring" board games.

Thank you all. To new beginnings.

Contents

Initial Proposal

This dissertation has as its base a software called WipFrag, which handles particle size analysis in quick fashion. WipFrag is said to be able to analyze instantly particle size from muck piles, from just one photograph, resulting in a grading curve based in customizable size classes. The results can later be displayed on Excel, PDF or even sent by e-mail.

Version 3 of WipFrag also includes BlastCast KCO, a fragmentation prediction module that provides better results regarding the size distribution.

The objetive of this dissertation is to study the capacity of WipFrag to analyze the particle sizes present in photographs, and compare the results to a regular, mechanical, sieving. As such, an introductory theory regarding mechanical and optical analysis should be provided, as well as an introduction to WipFrag.

In order to perform the laboratory trials, a procedure should be previously prepared, followed by the stages of sieving, photographs, software analysis and results discussion.

Abstract

The mining industry is at the base of the world's development, as it presents itself as a supplier for every other industry, as well as its own. The raw material provided my mines, as well as quarries, are widely used. Either in the pharmaceutical industry or the metallurgical industry, or even in the textile industry, its presence is always felt.

When talking about the development provided by the mining industry's products, it is also important to talk about the development within the mining industry itself. One of those developments, that has been gaining importance over the past years, is the use of optical analysis to infer granulometry.

The use of optical analysis to infer a granulometry is not a new idea, as it has been developed for over 30 years. One of the pioneers to develop a software that was able to perform an image analysis was the University of Waterloo, in 1986, by developing a software called WipFrag.

An idea came up to study whether or not WipFrag's capabilities were as accurat as other studies suggest. Using provided material from the mining department, the first stage of the study was to sieve the material, in order to later compare it with the results obtained from WipFrag. The following step was to photograph the material in different angles and conditions, and later, run those photographs through WipFrag. Finally, the last stage, was to compare the results provided by WipFrag and the ones from the initial sieving.

Keywords: mining industry; development; optical analysis; WipFrag

1. Introduction

The world is fueled by constant inovation, which brings an increasing need for raw materials. Most of those materials are obtained by the mining industry. For that reason, and the world's evolution goes hand in hand with the supply offered by the mining industry.

Nonetheless, even if there's a demand for a certain product, and there's a known reserve for such product, sometimes the economical feasibility isn't there. Whether it's by a small amount or a large amount, the mining industry needs to turn a profit from the investment. That is where progress comes to play, more accurately, the development of the technology available to the mining industry.

The development of the technology will allow mining companies to reduce costs in areas such as equipment, maintenance, workers, energy, water, and other resources, and/or increase the efficiency of the processes, which may be just enough to make a reserve ecomomically feasible, when once it was not.

One of the most important properties, when handling particles, is the particle size. Therefore, finding ways of making the particle size classification processes cheaper and more efficient is very important.

This dissertation is presented within the Master's Degree in Mining and Geo-Environmental Engineering of Faculdade de Engenharia de Universidade do Porto

The dissertation advisors were:

Jose Manuel Soutelo Soeiro de Carvalho

2. Mechanical particle size analysis

2.1 Fragmentation

The first big operation required to obtain the concentrate is the fragmentation. The type of fragmentation used is based on the process that is going to be used for the concentration of the ore, as each process requires different intensities of fragmentation. As such, what can be called the main problem of the preparation of ore is “the necessity to promote the release of mineral species from the ore”. (Leite).

Also, the need for fragmentation is a consequence of ulterior use.

2.2 Importance of particle size

The particle size is a property that is common to every particle that the treatment processes will handle. Many specifications related to processes are based on particle size, which may impact results of the processes and their efficiency. Needless to say that the correct calculation of the size of the particle required for these processes is of the utmost importance, as well as the maintenance and constant evaluation of the fragmentation processes, in order to guarantee the constant stream of material with the wanted particle size.

The importance of the control of the particle size is one of the reasons for the development of this thesis. It’s incredibly important to control the particle size, not only at the start of the fragmentation process, but also during every other process that either requires particle size control, or particle size alteration.

That control can be defined as “classification”, which is what is called to the operations in between the processes, to sort the particle sizes, thus optimizing the processes that concentrate the ore.

It is important to note that the particle size control is important for a high number of chemical, as well as physical, processes. For some cases, the size of the particle defines the final product, and therefore its value, which is another way of saying that if the particle doesn’t have the desired size, it will be a loss for the company. A fine example of the case mentioned above is gravel, whose economical value depends on the strict adherence to granulometric size properties.

Particle size analysis will not only affect the forementioned ore concentration processes, but also other processes, and even industries.

The size control of the product of blast operations, frequently the first fragmentation step, is very important to assess the blast itself, but also to assess the input material for further processes.

2.3 Expenditure control

A particle that goes through its first stage of classification may already have the desired size, even if it did not show during the classification stage, being thus important to guarantee a well planned and efficient classification process. This will allow a reduction of the costs, at various levels, such as:

- Energy consumption, which will lower, as the same particle won’t have to go through an unnecessary fragmentation process;
- Flow of material, which will increase, as particles won’t have to go through the fragmentation cycle again, thus giving space for new ones to take their place;

- Maintenance, which will see its costs lower, due smaller circulating charges, resulting in a higher economic recovery of the equipment;
- Equipment cost, which will lower, as the process can be planned in a way that avoids unnecessary fragmentation.

In regard to the blast operations, a proper size distribution control will lead to a better understanding of the blast, and its production, size wise. This will lead to better efficiency, which leads to a reduction of costs related to equipment and energy consumption.

2.4 Equipment

There are a few parameters to take into consideration when choosing the equipment to screen the material. Special attention must be given to:

- Type of material;
- Shape;
- Size;
- Quantity of material;
- Screen media openings;
- Harmful materials;
- Water requirements.

The equipment is all carefully chosen and calibrated. For that reason, as well as the high cost of the equipment, there is a high need to control the entire process, starting with the feed size distribution.

3. Optical particle size analysis

In order to have the crushing and grinding circuits running smoothly and efficiently, some parameters need to be optimized.

One of those parameters is the feed size distribution. Feed size distribution had been close to impossible to keep track of before optical screening came along. The other known way to keep track of the feed size distribution was regular mechanical screening, which is both time and money consuming, and therefore inadequate, thus seldom performed.

Before optical analysis came along, the method used, to measure feed size distribution, was to stop the circuit, proceed to retrieve a sample, sieve the sample, weigh each screen and, finally, plot the data retrieved. Not only was this process slow and disruptive, the results obtain were not very representative, as the sample had to be small.

The first optical analysis system to come along was WipFrag. It offered a faster and easier method of feed size distribution analysis, as well as being a practical software to analyze any material that can be imaged, and non-disruptive.

3.1 Measurement

The idea of optical screening, or sizing, is a great concept, albeit extremely complex.

Being magnitude independent, it can be used to measure the size distributions of blasted rock, the material on conveyor belts or in dumpers.

3.1.1 In situ

Out of the three uses mentioned, the easiest one is the first, the measurement of size distributions of blasted rock. This measurement is performed in situ.

Figure 1 - Muck pile imaging (source: Optical sizing analysis of blasted rock: lessons learned)

It's possible to see in the figure that there's a scale bar in the foreground, which allows to properly analyse the distribution with WipFrag.

Despite being the easiest way of measuring the material, it's not void of errors. As Maerz and Zhoud studied, in 1999 and 2001, the three most important factors to improve accuracy of the measurements were:

- Image quality, including uniform and constant lighting;
- Fixed scale of observation;
- Elimination of sampling biases.

Image quality relies on the lightning conditions, which revolve around the sun and clouds mostly, making this factor a somewhat easy task to get around, with the proper setup.

The scale of observation is also another factor that can easily fixed, as it depends on the distance and optical characteristics of the camera.

Even though the first two points can be achieved with some ease, the last is a strenuous task, due to the segregation in the pile.

3.1.2 Conveyor belt

The second use mentioned was the conveyor belt imaging.

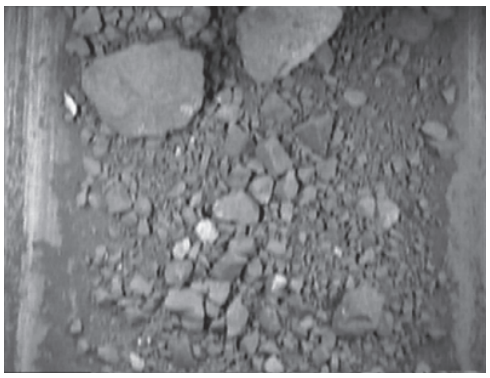


Figure 2 - Conveyor belt imaging (source: Optical sizing analysis of blasted rock: lessons learned)

Whilst the first use referred had some issues related with image quality (lighting), scale of observation and sampling bias, the conveyor belt measurement is a straightforward method that can easily ignore the previous issues, as artificial lights can be placed surrounding the conveyor belt, as well as a mounting system for the camera, and finally, the sampling bias is also reduced, as studied and attested by Maerz (2001), Elliot et al. (1999), Bouajila et al. (2000) and Dance (2001).

Maerz, however, does refer one difficulty associated with conveyor belt measurement to assess the blast size distribution, due to the fact that the blast size distribution would already be altered, as most circuits only start using conveyor belts past the first stage of crushing. The origin of the material will also be unknown, as materials tends to be put together, making it hard to track which comes from which blast.

A few modifications are needed software wise when moving from a manual read, as the measurement in situ (of the blast) or the measurement on dumpers. These are mostly due to the automation of the circuit, leading to the inability of

manual edition of images, or the elimination of images. Maerz points out three modifications that allow a correct conveyor belt measurement, using an optical screening software, such as WipFrag. These are:

- Mechanism that eliminates inappropriate images, for when the belt stops, is empty, or obscured by dust;
- Robust edge detection, due to the inability of manual edition of up to 5 analysis per second;
- Real time reporting system, with contingency plans.

The first point has three workarounds available, two of which for the empty or stopped belt situation, using TTL or OPC, and one for belts obscured by dust, which can also be used for empty belts, which is the use of software filters to identify the inappropriate images by their spectral characteristics, as Maerz suggests.

Figure 3 - Imaging setup (source: Automated Online Optical Sizing Analysis)

Maerz also suggests a few reporting systems that can set alarms off when certain conditions are met, which will not be mentioned in this dissertation, as those conditions and fail-safes are not the study subject.

The figure on the left shows an example of an image setup, specifically the setup from COREM, where both the artificial lightning and camera are visible, allowing a proper and stable read, without fluctuations in the light and camera angle.

3.1.3 Dumpers

The third, and final, use mentioned was the measurement of the material on dumpers.

Measurement of the material on dumpers is seen as a workaround to the problems encountered by the conveyor belt measurement, distribution alteration and unknown source. It is possible to take multiple images of the loading process happens, as well as when the unloading occurs.

A few alterations to the software are suggested by Maerz, to allow a proper execution of the measurement on dumpers. These are:

- Ability to sense a sample;
- Ability to wake up from sleep mode;
- Ability to identify the vehicle, and therefore the origin of the material;
- Ability to determine the volume of material present;
- Ability to image the loading bucket;
- Ability to discard parts of the image that lack material;
- Ability to analyze the image with an advanced fragmentation analysis system;
- Ability to collect the information in a database;
- Ability to share the information;
- Ability to enter sleep mode if no activity is detected.

Figure 4 - Dumper imaging (source: Optical sizing analysis of blasted rock: lessons learned)

As the technology, system and conditions that lead to the alterations suggested by Maerz are not part of the study subject, it will not be mentioned in this dissertation.

The constant development of technology leads to a beneficial use of optical sizing, as it allows its use where it is found to be best, which is in transit (dumpers), after being removed from the muck pile, and before the first stage of crushing, as proved by Palangio, Palangio and Maerz.

3.2 Benefits and limitations

In light of the extreme disadvantages of mechanical screening, optical screening offers a plethora of advantages (Maerz 2001), such as:

- Fraction of the cost, when compared to mechanical screening processes;
- Considering the non-existent additional costs when performing extra measurements, it's possible to perform a large number of measurements, allowing a better analysis of the material, without extra costs;
- Reduction of the losses caused by production inefficiency;
- Optical screening is a non-destructive screening method;
- Size offers no influence over the analysis, allowing both small and large particles to be screened;
- Offers no disruption to the production cycle;
- Analysis is performed quickly;
- The whole process is automatic.

There are also a few limitations related to optical screening (Maerz 2001), such as:

- Lack of accuracy;
- Inability to measure fines.

The limitations mentioned are usually related to a variety of sources (Maerz 2001):

- Method of analysis of the images;
- Sample presentation;
- Imaging process;
- Sampling process.

These limitations are further detailed by Norbert H. Maerz (2001), who properly defines each error. Maerz defines each error thoroughly, for a conveyor belt online optical sizing analysis.

“Errors related to the method of analysis of the images are ones caused by improper identification of blocks, and incorrect two to three dimensional transformation.” (Maerz 2001)

“Errors related to sample presentation relate to the lay of the individual blocks, especially if anisotropic.” (Maerz 2001)

“Errors related to the imaging process are concerned with all the technical aspects of imaging.” (Maerz 2001)

“Errors related the sampling process allude to the fact that not all fragments of rock can be sampled, so errors occur when the rocks that are sampled are not representative.” (Maerz 2001)

3.3 WipFrag

3.3.1 History

WipFrag was developed at the University of Waterloo, in 1986. It pioneered the image-based particle size analysis software. It was the first system that allowed optical sizing, and its advantages over mechanical methods were evident, as it was incredibly faster and easier to use.

As expected, its interface has suffered a plethora of alterations during the years, and it has also gained plenty new functions.

The initial program was a command-line application, that ran on DOS, back in the floppy discs days.

In current days, WipFrag is not only ran on Windows, but also on iOS, allowing images taken with an iPad or iPhone, or any other camera, to be analyzed.

3.3.2 User Interface

WipFrag has a straightforward UI, for both the Windows and iOS versions, both incredibly similar, which results in a better user adaptability. It is also a very simplistic UI, hiding from plain sight some of the more complex tools it can offer.

As soon as WipFrag is open, a window is show with a few options on the top, one of which is “New Analysis”, displayed by a “+” icon, on the top right side of the window. After selecting the icon, a few new options are available. For an iOS device, it is possible to take a new picture and perform the analysis in situ. There are other options available, one of which is opening an existing image, previously taken, or a demo image, for testing purposes.

After importing the desired images, it is possible to enter each image individually and check for details, such as GPS and Camera information, if available.

The top right of the window is also replaced by a new tool menu, with four options available. The first one, from the left, is the scale tool, followed by the filter settings, the manual editing tools, and, finally, the chart analysis.

The chart displays the granulometric curve obtained from the analysis, along with some more information, such as the passing and retained percentages, the D’s of certain sizes and the sphericity. The information displayed can be changed, as WipFrag allows adding or removing information, from both the curve and the graphic text box.

3.3.3 Versions

WipFrag is a technical software IP. As such, it’s only used by a small niche of Windows and iOS users, which leads to a hetfy price tag.

It currently boasts a portfolio with three different versions, which mostly differ in what each offers.

According to WipFrag's parent company webiste, wipware.com, the three configurations, and what each offers, is:

Table 1 - WipFrag's configurations

	iOS (App Version)	Windows (Software License)	Windows (Hardware License)
Price (USD)	999	4,995	5,995
GeoTiff Support		X	X
Auto Scale	X		
Network License Sharing		X	
Digital Delivery	X	X	
Large UAV Image Support	X	X	X
GIS/UAV	X	X	X
GPS Metadata	X	X	X
iCloud Drive Support	X	X	X
WipWare System Interface	X	X	X
BlastCast	X	X	X
Irregularity Detection	X	X	X

Additional notes:

- Price - USD, tax, duties and shipping (if applicable) not included
- GeoTiff Support - Open orthomosaic images with embedded location information
- Auto Scale - Snap pictures without a physical scale
- Network License Sharing - Computers on the same network run WipFrag (1 concurrent)

- Digital Delivery - No shipment required
- Large UAV Image Support - Open UAV/Orthomosaic images tp to 16 MP
- GIS/UAV - Display merged heatmap information
- GPS Metadata - Open images with embedded GPS information
- iCloud Drive Support - Allow WipFrag data to sync to iCloud Drive
- WipWare System Interface - Remotely view and configure WipWare Automated Systems
- BlastCast - Enter blast info and display fragmentation predictions
- Irregularity Detection - Detect irregular material based on color

3.3.4 Benefits

Not only is optical analysis used by the mining industry, it is also used by other industries, such as the explosives industry. The one thing those industries have in common is the need to improve efficiency of the comminution process.

Considering the widespread usage of software for optical fragmentation sizing, it is important to offer a complete software for the industry needs. According to WipFrag's parent company webiste, wipware.com, the benefits of using WipFrag are:

- Non-contact;
- Non-disruptive;
- Detect irregularities;
- Establish quality control;
- Characterize geology;
- High accuracy;
- Instant results;
- Improve safety;
- Increase throughput;
- Reduce maintenance;
- Reduce re-handling;

- Reduce dilution;
- Reduce waste;
- Improve fragmentation;
- Objetive quantification.

4. Trials

In order to study the particle sizes using image analysis, several analysis were made, using the same sample lot.

Each analysis was performed by placing the sample on top of a black paperboard sheet, and taking pictures of the respective sample, from multiple angles.

An extra light source was also used, as the experiment was made indoors, and the light source was a way to mimic the outside light conditions, providing better and stronger lightning. At least one picture in each of the sets was also taken without the use of the extra light, allowing to compare the results of the analysis with and without the light.

One other important factor for the correct usage was Wipfrag was the addition of a measurement element to each photograph, which serves as the scaling unit.

A total of 5 different picture sets were taken.

- Set number 1 had seven photographs. It was displayed as a stack;
- Set number 2 had eleven photographs. It was displayed as a single layer;
- Set number 3 had nine photographs. It was displayed as a single layer;
- Set number 4 had twelve photographs. It was displayed as a single layer;
- Set number 5 had twelve photographs. It was displayed as a stack.

All the sets were randomly placed, either as a layer or a stack. The placement was performed in a way that guaranteed that the particles would be randomly displayed, and not stacked by size class.

Previously, the material had been mechanically sieved, allowing a comparison with the results obtained with the software.

During the software analysis, the filter automatic settings that seemed most adequate, which means that seemed to cover most particles properly, was used.

Later, the results obtained were compared with the results previously obtained in the mechanical sieving.

Advanced filter settings were not used during the analysis. Manual particle edition was also not used for the set analysis, as it was pratically impossibly to perform manual edition of all the images within the time constraints.

4.1 Test trial

Before the main trial, a test trial was performed, not only for a better understanding on the software, but also to study the best way to display and photograph the material.

The test trial initially consisted of mechanically sieving the material, to later compare it with the optical analysis.

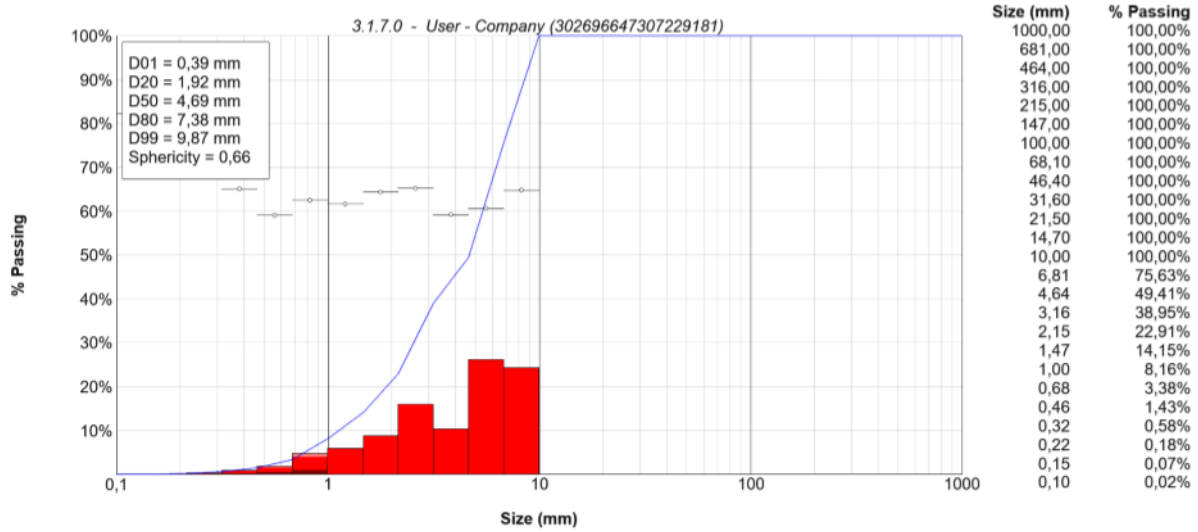
Afterwards, the material was placed in a table. It was randomly placed, in an attempt to avoid sampling bias. After placing the material in the table, photographs were taken, and later analyzed with the software.

A few issues were encountered. The first was that the software filter included the table in the analysis, as it was not a plain table, which resulted in a few unnecessary additions to the analysis.

The second issue was the lack of a physical and clearly visible scale. One of the particles was measured, and it was as the scale, which was not the best option.

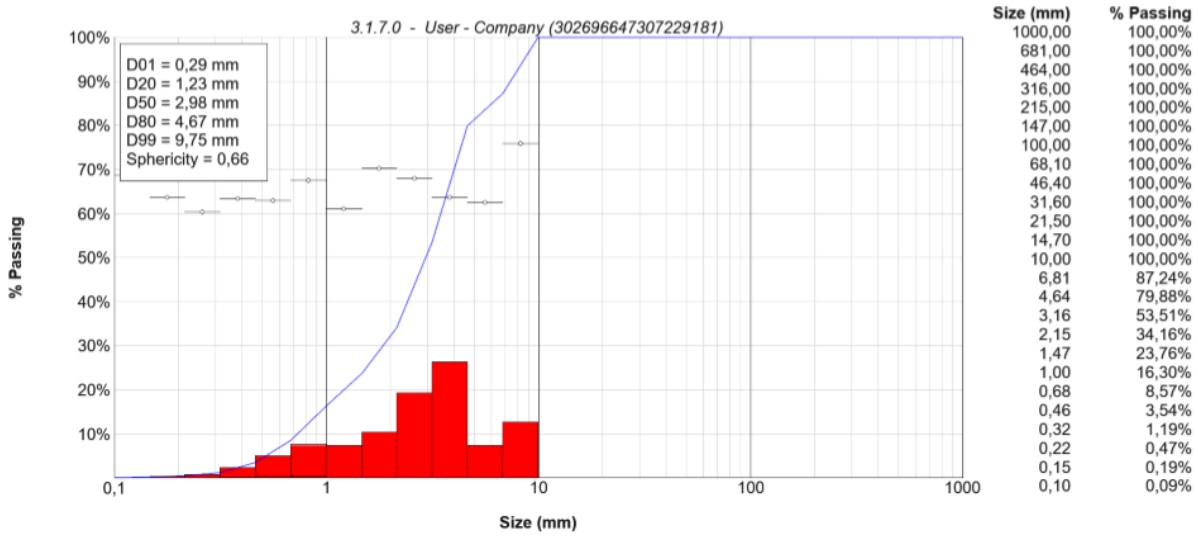
The final issue encountered was a simple one to solve, although it was only discovered later, after a second test trial was performed. It consisted of using the wrong unit in the scaling tool. It was marked as 4mm, instead of 40mm, or even 4cm. Even though it was an issue that could easily be resolved, as there were

other issues found during the trial, the first test trial was discarded. Nonetheless, the results obtained are displayed below.



Size (mm)	% Passing
1000,00	100,00%
681,00	100,00%
464,00	100,00%
316,00	100,00%
215,00	100,00%
147,00	100,00%
100,00	100,00%
68,10	100,00%
46,40	100,00%
31,60	100,00%
21,50	100,00%
14,70	100,00%
10,00	100,00%
6,81	75,63%
4,64	49,41%
3,16	38,95%
2,15	22,91%
1,47	14,15%
1,00	8,16%
0,68	3,38%
0,46	1,43%
0,32	0,58%
0,22	0,18%
0,15	0,07%
0,10	0,02%

Figure 5 - First test trial analysis 1



Size (mm)	% Passing
1000,00	100,00%
681,00	100,00%
464,00	100,00%
316,00	100,00%
215,00	100,00%
147,00	100,00%
100,00	100,00%
68,10	100,00%
46,40	100,00%
31,60	100,00%
21,50	100,00%
14,70	100,00%
10,00	100,00%
6,81	87,24%
4,64	79,88%
3,16	53,51%
2,15	34,16%
1,47	23,76%
1,00	16,30%
0,68	8,57%
0,46	3,54%
0,32	1,19%
0,22	0,47%
0,15	0,19%
0,10	0,09%

Figure 6 - First test trial analysis 2

The mechanical sieving results were:

Table 2 - Sieving results of the first test trial

Size (mm)	Weight (kg)	Retained (%)	Passed (%)
			100
37,50	0,05269	2,07	97,93
26,5	0,51491	20,24	77,69
25	0,16902	6,64	71,05
19,00	0,85245	33,51	37,54
13,20	0,75081	29,51	8,03
9,50	0,18664	7,33	0,7
6,70	0,01593	0,62	0,08
<6,70	0,00133	0,0522	0,0278

Due to the issues encountered, a second test trial was conducted, this time in a pan.

The procedure was similar to the first test trial. The material was mechanically sieved, as it was a different batch (of the same material), to later compare it with the optical analysis.

The material was then placed in a pan. As in the first trial, it was randomly placed, in an attempt to avoid sampling bias. Photographs were taken, and later analyzed with the software.

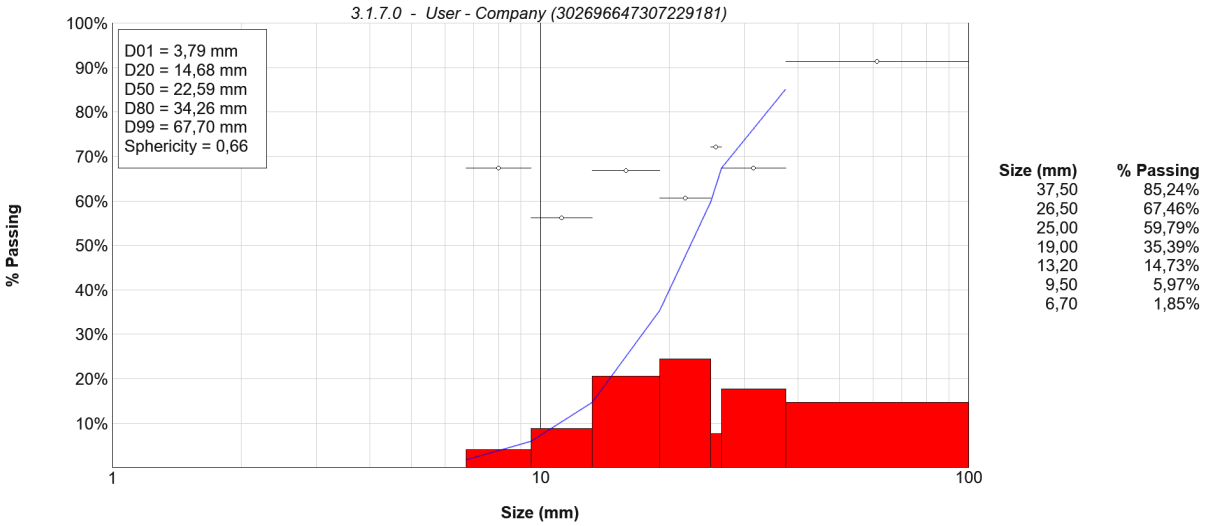


Figure 7 - Second test trial analysis 1

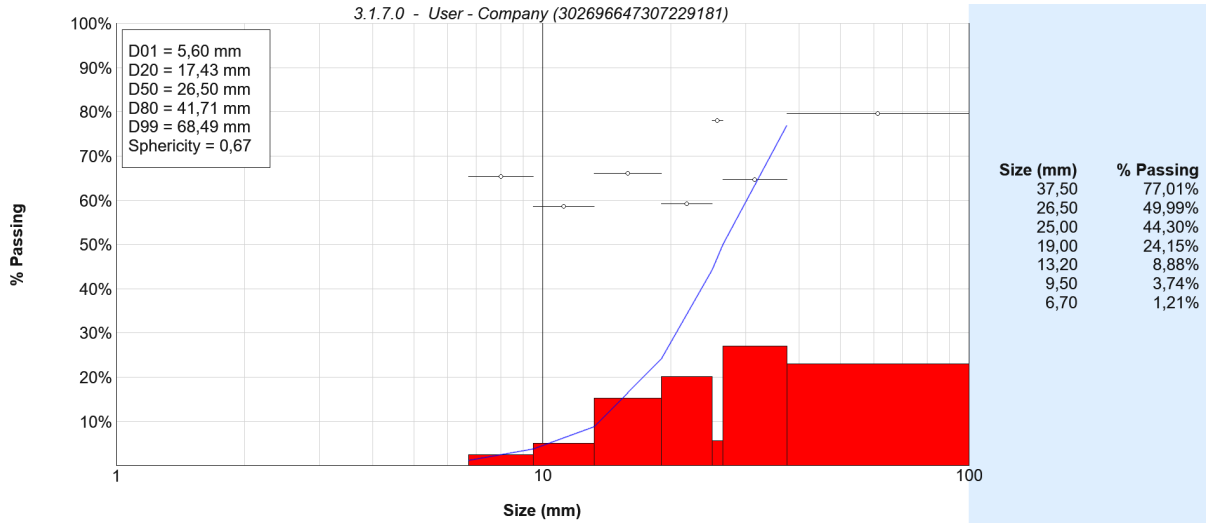


Figure 8 - Second test trial analysis 2

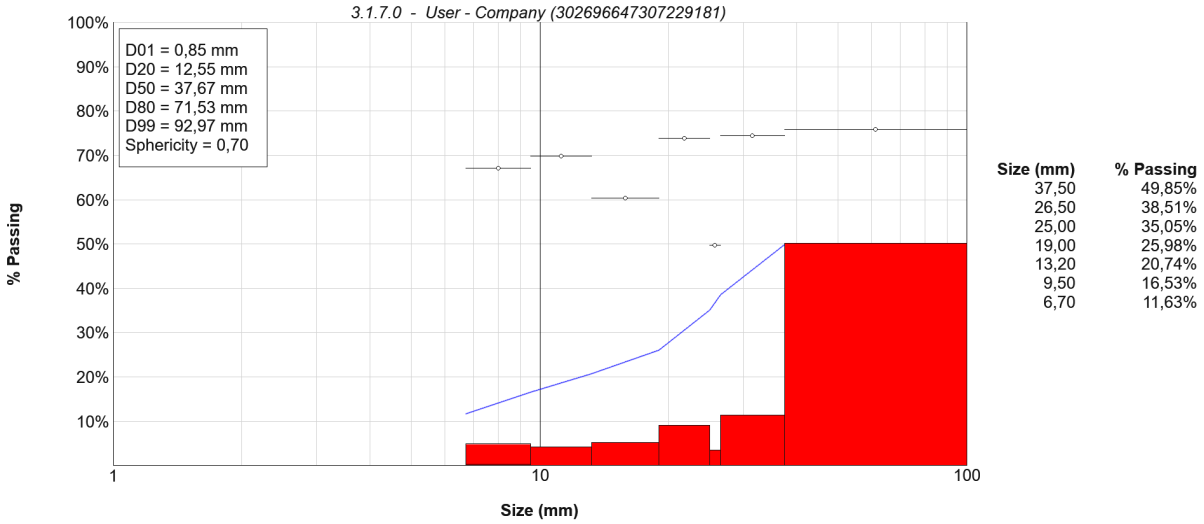


Figure 9 - Second test trial analysis 3

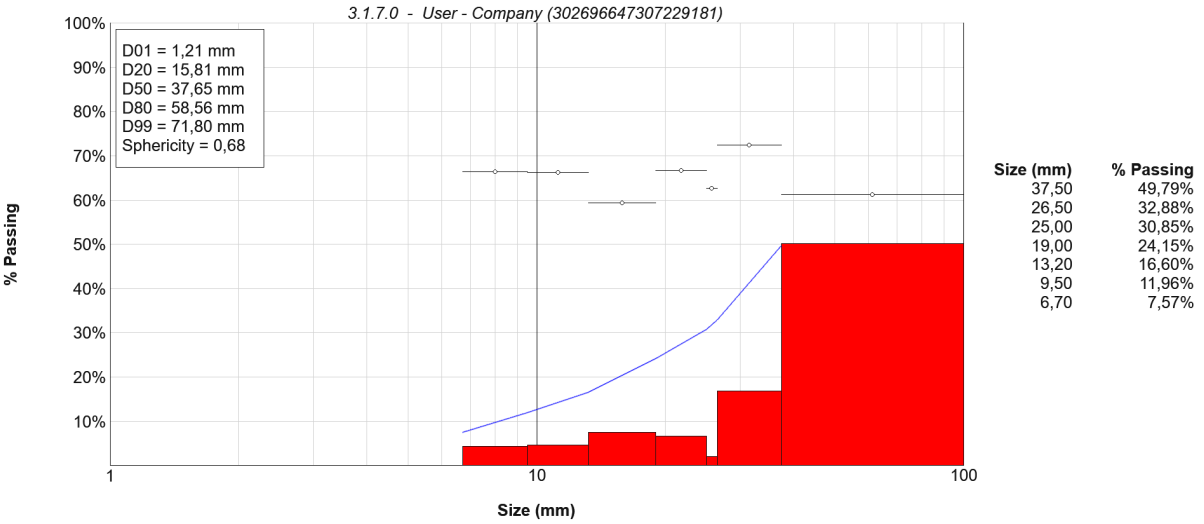


Figure 10 - Second test trial analysis 4

The results for analysis 1 and 2 are the results of a manual particle edition.

The mechanical sieving results were:

Table 3 - Sieving results of the second test trial

Size (mm)	Weight (kg)	Retained (%)	Passed (%)
			100
37,50	0,33	12,00	88
26,5	0,47	17,09	70,91
25	0,27	9,82	61,09
19,00	0,77	28,00	33,09
13,20	0,67	24,36	8,73
9,50	0,20	7,27	1,46
6,70	0,03	1,09	0,37
<6,70	0,01	0,36	0,01

Table 4 - Second test trial passing % analysis comparison

Size (mm)	Sieving	Analysis 1	Analysis 2	Analysis 3	Analysis 4
	100				
37,50	88	85,24	77,01	49,85	49,79
26,5	70,91	67,46	49,99	38,51	32,88
25	61,09	59,79	44,30	35,05	30,85
19,00	33,09	35,39	24,15	25,98	24,15
13,20	8,73	14,73	8,88	20,74	16,60
9,50	1,46	5,97	3,74	16,53	11,96
6,70	0,37	1,85	1,21	11,63	7,57
<6,70	0,01				

Comparing the sieving results to the analysis 1 results, it is possible to see notice the similarity in the values. This accuracy was expected, as Analysis 1 of the second test trial is based on a manual edition of the photograph, which did not happen for the other analysis, due to time constraints.

Even though the results from analysis 2 are not as similar to the sieving results as the ones from analysis 1, the results obtained are very satisfactory, as the anal-

ysis was performed with the automatic filter, which provided a good accuracy.

Analysis 3 and 4 were performed with the filter setting tool “Best Fit”, which not only was not optimal, as it included the other aspects of the photograph leading to inaccurate results, it was also time consuming.

4.2 Equipment and software used

4.2.1 Equipment

The camera used was the back camera of an *One Plus 3*. Its specifications are:

- 16 MP IMX298, f/2.0, 1/2.8”, 1.12Âµm, OIS, PDAF

The light used for the photographs was supplied by two tripod site lights, already available at the laboratory.

The laboratory mesh (sieves) and pan used were by Retsch.

Figure 11 - Tripod site light

Figure 12 - Sieve and pan

4.2.2 Software

The software used for the optical analysis was *Wipfrag*.

The version was 3.1.7.0. At no point during the trials was the software updated.

4.3 Wipfrag results

The following chapter will show the granulometric curves, and respective information, obtained from the WipFrag optical analysis.

The information obtained was later used to perform a few other analysis, in an Excel spreadsheet. Those analysis included an outlier analysis, which is represented in this dissertation, as well as granulometric curves comparisons, retained and passed percentages, and comparisons regarding the lightning conditions.

4.3.1 Set number 3

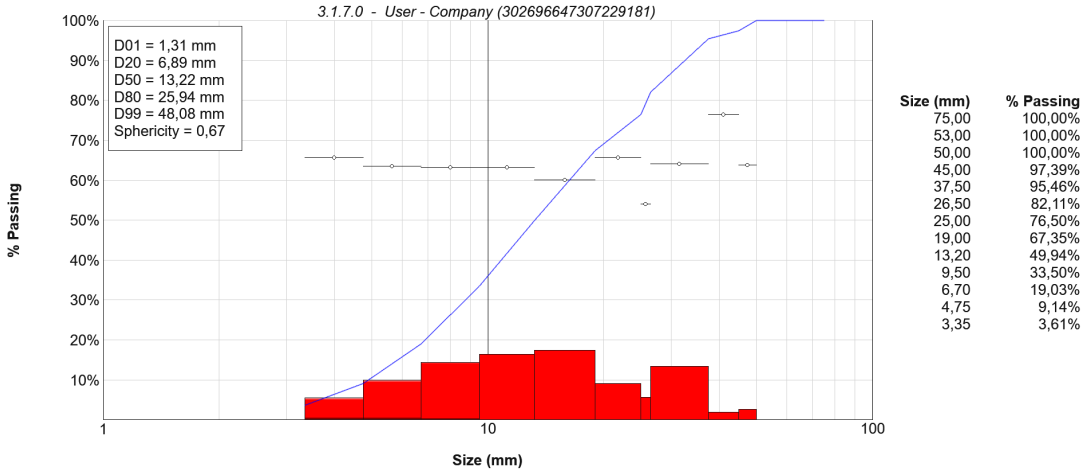


Figure 13 - Results set 3 image 1

4.3.2 Set number 4

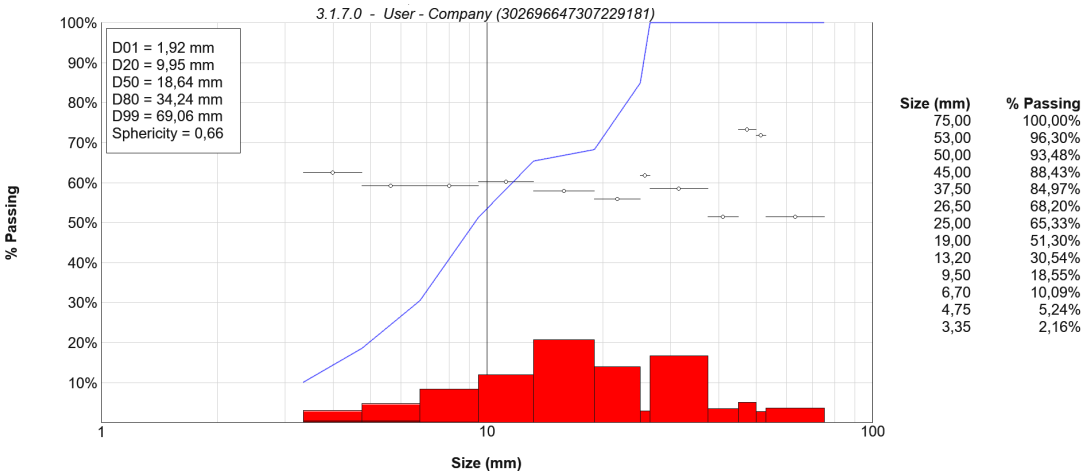


Figure 14 - Results set 4 image 1

4.3.3 Set number 5

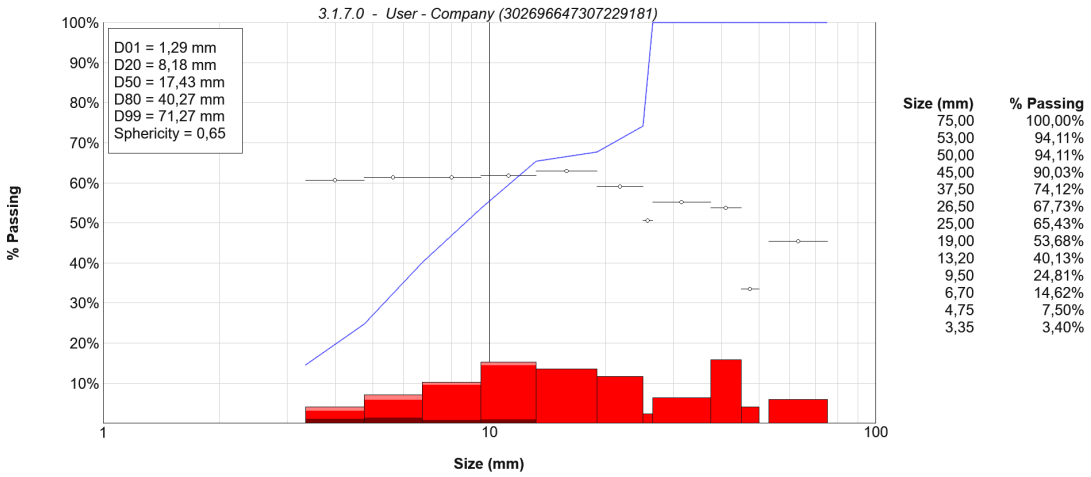


Figure 15 - Results set 5 image 1

4.4 Wipfrag image analysis study

For set number 3, image number 7 and image number 8 were submitted to an extra analysis, “Best Fit”, the first of which resulted in a 84,3% “Best Score”, and the latter a 84,1% “Best Score”.

For that same set, set number 3, image number 4 was submitted to a faster filter, also called “Best Fit”, but the standard version. The result was a “Best Score” of 90,6%.

Considering the three extra image analysis, a total of twelve image analysis were performed for set number 3.

The extra analysis, previously referred as “Best Fit”, is an automatic analysis performed by Wipfrag, which renders the entire image and comes up with the best values for each of the following parameters: Threshold, Valley Threshold, Blur, Search Dark, Search Radius, Window Size.

Even though it’s called “Best Fit”, during the experiments a problem came up, which prevented the correct rendering of the photograph, therefore resulting

in an incorrect particle size analysis. The problem encountered was the background of the image, and two solutions were found. One was the removal of the background, using the software's own background removal tool, which added another problem, as it can remove particles from the image, if any particle isn't completely covered by the lines, leading to a manual input from the user, to close the lines.

The second solution that was found was a close up of the photograph. This solution also added a few problems of its own, ranging from the need to adjust the scaling, as well as the unit used, and the exclusion of some particles from the analysis, which can be compromising to the final particle size analysis.

Before comparing the software image analysis results to the actual mechanical analysis results, the procedure for the latter must be thoroughly explained.

The mechanical analysis was performed at FEUP, in the Mining Engineering Department's laboratory. The material utilized was already available in the laboratory, consisting in fragmented granite, previously fragmented in that same laboratory. The screening was done mechanically, and each particle, up until 3,35mm was tested in each mesh, in order to make sure it was in its correct size class. The mesh sizes utilized were as follows, in millimeters: 75,00; 53,00; 50,00; 45,00; 37,50; 26,50; 25,00; 19,00; 13,20; 9,50; 6,70; 4,75; 3,35.

The material was divided in lots, and placed in the sieves, each lot at a time, in order to facilitate the sieving process and obtain better results. Two sieve shakers were used, one with the lower sizes, and the other with the higher sizes. After running one lot through the sieve shaker that contained the higher sizes, which lasted for 30 minutes, that lot would go through to the other sieve shaker, with the lower sizes, while a new lot would go to the previous sieve shaker, with the higher sizes. This way, not only was the sieving process faster, due to the usage of two sieve shakers, it was also more efficient, as the division in lots allowed for a better mechanical analysis.

The weight of the material was weighed to be 5,11kg.

The optical analysis of set number 1 and number 2 was excluded, as the photographs did not have a scale item present, rendering the correct analysis non pratical, as it could lead to an incorrect level of accuracy of the results.

The result for the mechanical sieving analysis were as follows:

Table 5 - Sieving results

Size (mm)	Weight (kg)	Retained (%)	Passed (%)
			100
75,00	0	0	100
53,00	0,14	2,7397	97,2603
50,00	0	0	97,2603
45,00	0	0	97,2603
37,50	0,18	3,5225	93,7378
26,50	0,49	9,5890	84,1488
25,00	0,48	9,3933	74,7554
19,00	1,11	21,7221	53,0333
13,20	1,64	32,0939	20,9393
9,50	0,69	13,5029	7,4364
6,70	0,28	5,4794	1,9570
4,75	0,05	0,9785	0,9785
3,35	0,03	0,5871	0,3914
<3,35	0,02	0,3914	~0,0000

The results for set number 3 Wipfrag image analysis were as follows:

Table 6 - Optical analysis of set number 3

Size (mm)	Weight (kg)	Retained (%)	Passed (%)
			100
75,00	0	2,6887	97,3113
53,00	0,14	8,5476	88,7636
50,00	0	1,5009	87,2627
45,00	0	3,9918	83,2709
37,50	0,18	5,1718	78,0991
26,50	0,49	17,7409	60,3582
25,00	0,48	2,9491	57,4091
19,00	1,11	12,9254	44,4836
13,20	1,64	14,8535	29,6301
9,50	0,69	11,2274	18,4027
6,70	0,28	8,5927	9,8100
4,75	0,05	5,3009	4,5091
3,35	0,03	2,6718	1,8373
<3,35	0,02	1,8373	~0,0000

The results for set number 4 Wipfrag image analysis were as follows:

Table 7 - Optical analysis of set number 4

Size (mm)	Weight (kg)	Retained (%)	Passed (%)
			100
75,00	0	3,1192	96,8808
53,00	0,14	7,4725	89,4083
50,00	0	1,8917	87,5167
45,00	0	3,5725	83,9442
37,50	0,18	6,8350	77,1092
26,50	0,49	19,0842	58,0250
25,00	0,48	2,9833	55,0417
19,00	1,11	13,6467	41,3950
13,20	1,64	17,0208	24,3747
9,50	0,69	10,6733	13,7008
6,70	0,28	6,9500	6,7508
4,75	0,05	3,5767	3,1742
3,35	0,03	1,8742	1,3000
<3,35	0,02	1,3000	~0,0000

The results for set number 5 Wipfrag image analysis were as follows:

Table 8 - Optical analysis of set number 5

Size (mm)	Weight (kg)	Retained (%)	Passed (%)
			100
75,00	0	3,1192	96,8808
53,00	0,14	7,4725	89,4083
50,00	0	1,8917	87,5167
45,00	0	3,5725	83,9442
37,50	0,18	6,8350	77,1092
26,50	0,49	19,0842	58,0250
25,00	0,48	2,9833	55,0417
19,00	1,11	13,6467	41,3950
13,20	1,64	17,0208	24,3742
9,50	0,69	10,6733	13,7008
6,70	0,28	6,9500	6,7508
4,75	0,05	3,5767	3,1742
3,35	0,03	1,8742	1,3000
<3,35	0,02	1,3000	~0,0000

The filter settings automatically set for each image were (Threshold; Valley Threshold; Blur; Search Dark; Search Radius, Window Size):

Table 9 - Advanced filter settings for each optical analysis

	Set 3	Set 4	Set 5
1	-40; -3,0; 0,5; 15; 15; 20	-60; -3,0; 0,5; 15; 15; 20	-40; -1,0; 1,0; 15; 15; 20
2	-60; -2,0; 1,0; 15; 15; 20	-60; -3,0; 0,5; 15; 15; 20	-50; -3,0; 0,5; 15; 15; 20
3	-30; -2,0; 1,0; 15; 15; 20	-40; -3,0; 1,0; 15; 15; 20	-60; -1,0; 1,0; 15; 15; 20
4	-50; -1,0; 1,0; 15; 15; 20	-50; -3,0; 0,5; 15; 15; 20	-60; -3,0; 0,5; 20; 5; 20
5	-60; -1,0; 1,0; 15; 15; 20	-60; -3,0; 0,5; 15; 15; 20	-60; -3,0; 1,0; 15; 15; 20
6	-60; -3,0; 0,5; 15; 15; 20	-60; -1,0; 1,0; 15; 15; 20	-50; -1,0; 1,0; 15; 15; 20
7	-40; -1,0; 1,0; 15; 15; 20	-50; -3,0; 0,5; 15; 15; 20	-50; -1,0; 1,0; 15; 15; 20
7 extra			-10; -1,0; 1,0; 15; 5; 25
8	-60; -3,0; 0,5; 15; 15; 20	-60; -3,0; 0,5; 15; 15; 20	-60; -1,0; 1,0; 15; 15; 20
8 extra			-10; -1,0; 1,0; 15; 5; 25
9	-60; -3,0; 0,5; 15; 15; 20	-60; -3,0; 0,5; 15; 15; 20	-60; -3,0; 0,5; 15; 15; 20
10	-30; -1,0; 2,0; 15; 15; 20	-60; -1,0; 2,0; 15; 15; 20	
11	-50; -1,0; 1,0; 15; 15; 20	-50; -3,0; 1,0; 15; 15; 20	
12	-40; -1,0; 1,0; 15; 15; 20	-60; -2,0; 1,0; 15; 15; 20	

To accurately study the influence of each photograph in the average value of the each set, the outlier elimination method was used.

A total of three different values for the outlier elimination process were considered, 20%, 15% and 10%. The 5% value was not considered as no image analysis had all values below a 5% difference in its equivalent of the mechanical analysis.

When considering the outlier values, the image analysis results of some photographs were cut out, from the respective set, and left out the respective outlier analysis. For example, for the value of 20%, set number 3 had image analysis “3 set _ 4 _ bestfit _ standard” excluded, leaving a total of 11 samples to consider for that set.

The image analysis excluded from each set, from each outlier value, were as

follows:

Outlier value of 20%:

Set number 3 excluded image analysis:

- 3 set _ 4 _bestfit _ standard

Set number 4 excluded image analysis:

- 4 set _ 10
- 4 set _ 12

Set number 5 excluded image analysis:

- 5 set _ 3
- 5 set _ 4
- 5 set _ 5
- 5 set _ 7

Outlier value of 15%:

Set number 3 excluded image analysis:

- 3 set _ 2
- 3 set _ 3
- 3 set _ 4
- 3 set _ 4 _bestfit _ standard
- 3 set _ 5
- 3 set _ 7
- 3 set _ 7 _ extrafullscan
- 3 set _ 8

- 3 set _ 8 _ extrafullscan
- 3 set _ 9

Set number 4 excluded image analysis:

- 4 set _ 2
- 4 set _ 8
- 4 set _ 9
- 4 set _ 10
- 4 set _ 12

Set number 5 excluded image analysis:

- 5 set _ 1
- 5 set _ 3
- 5 set _ 4
- 5 set _ 5
- 5 set _ 7
- 5 set _ 8
- 5 set _ 10
- 5 set _ 11

Outlier value of 10%:

Set number 3 excluded image analysis:

- 3 set _ 1
- 3 set _ 2
- 3 set _ 3
- 3 set _ 4
- 3 set _ 4 _bestfit _ standard

- 3 set _ 5
- 3 set _ 6
- 3 set _ 7
- 3 set _ 7 _ extrafullscan
- 3 set _ 8
- 3 set _ 8 _ extrafullscan
- 3 set _ 9

Set number 4 excluded image analysis:

- 4 set _ 1
- 4 set _ 2
- 4 set _ 3
- 4 set _ 4
- 4 set _ 5
- 4 set _ 6
- 4 set _ 7
- 4 set _ 8
- 4 set _ 9
- 4 set _ 10
- 4 set _ 11
- 4 set _ 12

Set number 5 excluded image analysis:

- 5 set _ 1
- 5 set _ 2
- 5 set _ 3
- 5 set _ 4
- 5 set _ 5
- 5 set _ 7

- 5 set _ 8
- 5 set _ 9
- 5 set _ 10
- 5 set _ 11
- 5 set _ 12

One detail that easily comes up regarding the excluded image analysis is the exclusion of the same analysis. That can be easily explained by the fact that if an image analysis is excluded because it does not meet the requirements for a certain outlier value, it will automatically not meet the requirements for the following outlier value, which is a lower value.

One other easily detected detail is the complete exclusion of every image analysis from both set number 3 and number 4, for the outlier value of 10%, whereas set number 5 still had one image analysis left, “5 set _ 6” for that same outlier value, therefore being the only relevant value for the sample at a 5% outlier value.

When analysing the original results for the image analysis of sets number 3, 4 and 5, the average Retained values are somewhat similar. In fact, the most noticeable difference is at size 75,00mm, where set number 5 has about a 4% difference from set number 3 and set number 4, being higher than the two, and then, again a difference between set number 5 and the other two sets, where it’s about 5% lower, at size 26,50mm.

Considering all the other values for each size, in each set, and the way they are all similiar to eachother, the 4 and 5% differences for sizes 75,00 and 26,50mm can easily be explained, as the set that has a higher value for one of the sizes later has a lower value for another size, leaving the rest of the values similar.

Table 10 - Trial Retained Comparison (no outlier)

Size (mm)	Sieving(%)	Set 3 (%)	Set 4 (%)	Set 5 (%)
75,00	0	2,6887	3,1192	3,1192
53,00	2,7397	8,5476	7,4725	7,4725
50,00	0	1,5009	1,8917	1,8917
45,00	0	3,9918	3,5725	3,5725
37,50	3,5225	5,1718	6,8350	6,8350
26,50	9,5890	17,7409	19,0842	19,0842
25,00	9,3933	2,9491	2,9833	2,9833
19,00	21,7221	12,9254	13,6467	13,6467
13,20	32,0939	14,8535	17,0208	17,0208
9,50	13,5029	11,2274	10,6733	10,6733
6,70	5,4794	8,5927	6,9500	6,9500
4,75	0,9785	5,3009	3,5767	3,5767
3,35	0,5871	2,6718	1,8742	1,8742
<3,35	0,3914	1,8373	1,3000	1,3000

By looking at the previous Trial Retained Comparison table for sets number 3, 4 and 5, which are compared to the mechanical analysis results, a pattern can easily be spotted. All three sets are higher than the mechanical analysis between sizes 75,00 and 26,50mm, and then again between sizes 6,70 and lower than 3,35mm. Between 25,00 and 9,50mm all three sets have a lower value than the mechanical analysis. When compared to the mechanical analysis, there is a clear gap between the mechanical analysis and the image analysis for set number 3, 4 and 5 at sizes 19,00 and 13,20mm, being the difference for the 13,20mm size considerable, and higher than 15,00% for all three sets. This difference is important and relevant to the general picture, as it will greatly shape the final form of the graphic, leading to a gap between the mechanical analysis value and each of the set values.

This difference can be explained in a few different ways. A few factors can influence the outcome of the analysis. The most important one, that had a clear

effect, were the camera angle, the lightning conditions, and the sampling bias.

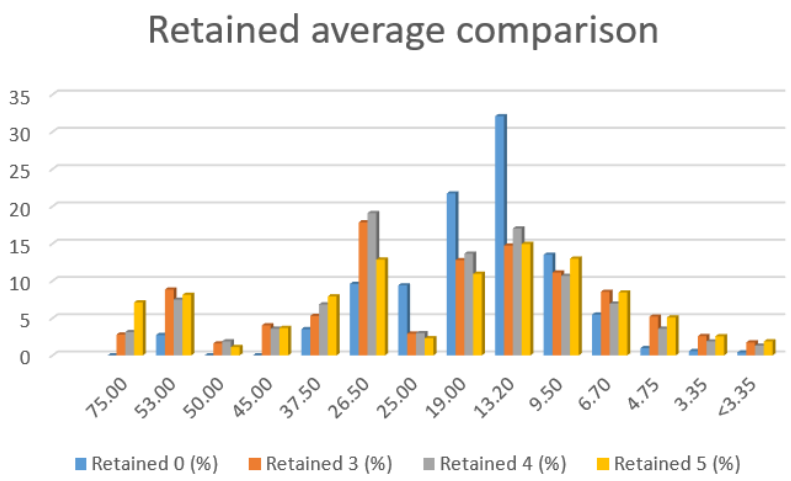


Figure 16 - Retained average comparison

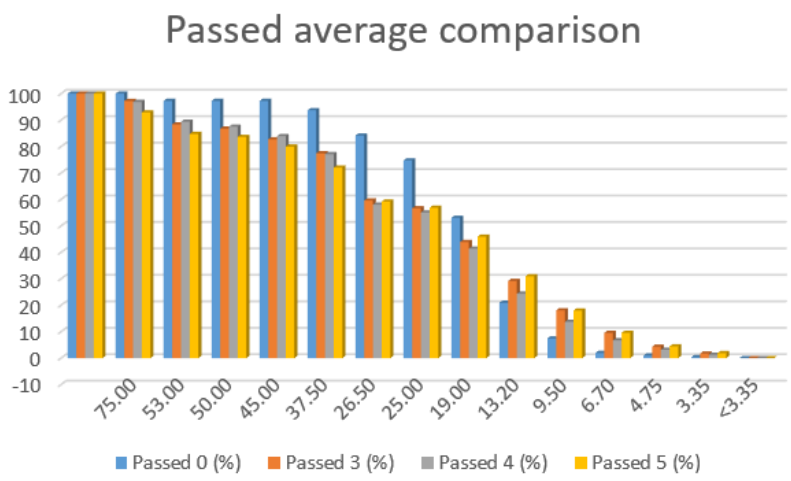


Figure 17 - Passed average comparison

Table 11 - Trial Retained Comparison (20% outlier)

Size (mm)	Sieving(%)	Set 3 (%)	Set 4 (%)	Set 5 (%)
75,00	0	2,6887	0,508	1,5025
53,00	2,7397	6,8367	6,001	4,8125
50,00	0	1,2073	1,671	1,2488
45,00	0	3,8764	3,537	4,1112
37,50	3,5225	4,72	6,661	7,7312
26,50	9,5890	15,5736	18,736	13,0975
25,00	9,3933	2,7327	3,133	2,5525
19,00	21,7221	11,9254	14,456	12,0025
13,20	32,0939	13,8308	18,554	17,08125
9,50	13,5029	10,4183	11,605	14,8625
6,70	5,4794	7,9982	7,593	9,4675
4,75	0,9785	4,9527	3,944	6,0513
3,35	0,5871	2,4864	2,117	3,095
<3,35	0,3914	1,6618	1,484	2,3838

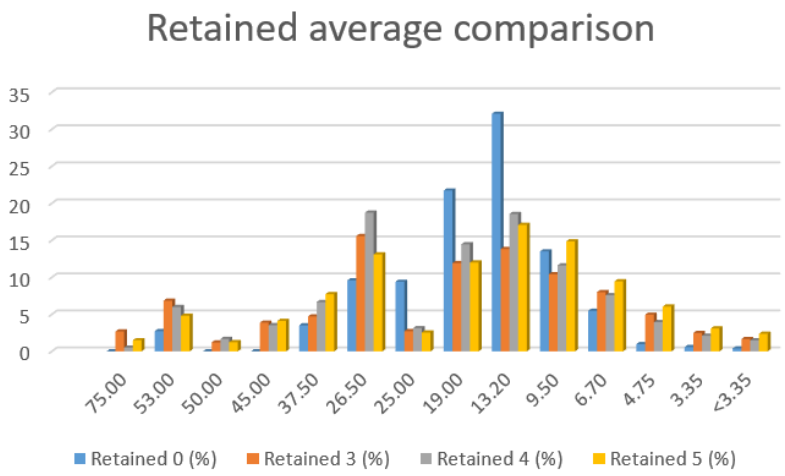


Figure 18 - Retained average comparison for a 20% outlier

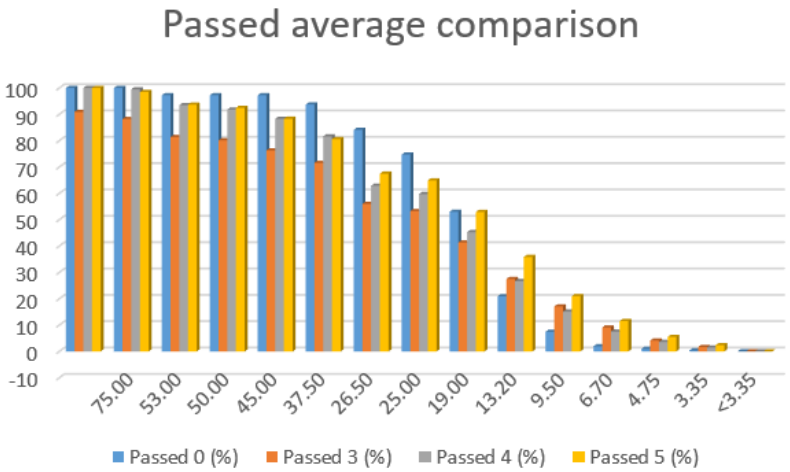


Figure 19 - Passed average comparison for a 20% outlier

Table 12 - Trial Retained Comparison (15% outlier)

Size (mm)	Sieving(%)	Set 3 (%)	Set 4 (%)	Set 5 (%)
75,00	0	0	0	0
53,00	2,7397	1,9233	4,6586	1,155
50,00	0	0	1,8671	0,7125
45,00	0	0,87	3,71	3,6425
37,50	3,5225	1,2367	5,96	5,5275
26,50	9,5890	10,3533	16,9986	10,64
25,00	9,3933	2,9533	2,8514	2,41
19,00	21,7221	7,5133	14,6629	13,26
13,20	32,0939	11,96	19,8171	20,9575
9,50	13,5029	9,42	12,5686	17,88
6,70	5,4794	8,3233	8,3657	11,0075
4,75	0,9785	6,06	4,4043	6,9275
3,35	0,5871	3,4967	2,5	3,3225
<3,35	0,3914	2,5567	1,6357	2,5575

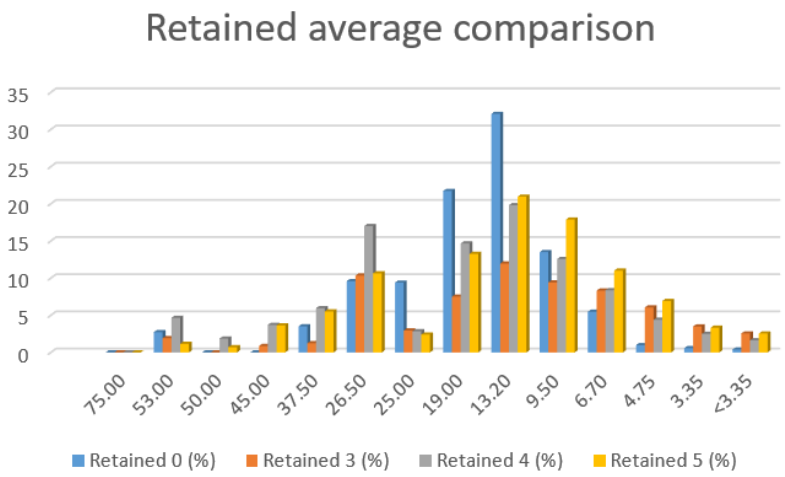


Figure 20 - Retained average comparison for a 15% outlier

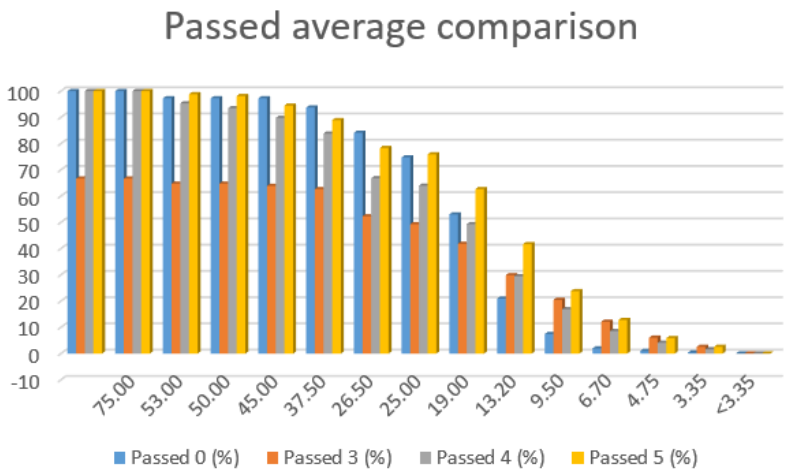


Figure 21 - Passed average comparison for a 15% outlier

Table 13 - Trial Retained Comparison (10% outlier)

Size (mm)	Sieving(%)	Set 3 (%)	Set 4 (%)	Set 5 (%)
75,00	0			0
53,00	2,7397			0
50,00	0			0
45,00	0			4,83
37,50	3,5225			7,23
26,50	9,5890			8,75
25,00	9,3933			2,72
19,00	21,7221			14
13,20	32,0939			24,55
9,50	13,5029			17,29
6,70	5,4794			8,67
4,75	0,9785			6,27
3,35	0,5871			3,28
<3,35	0,3914			2,41

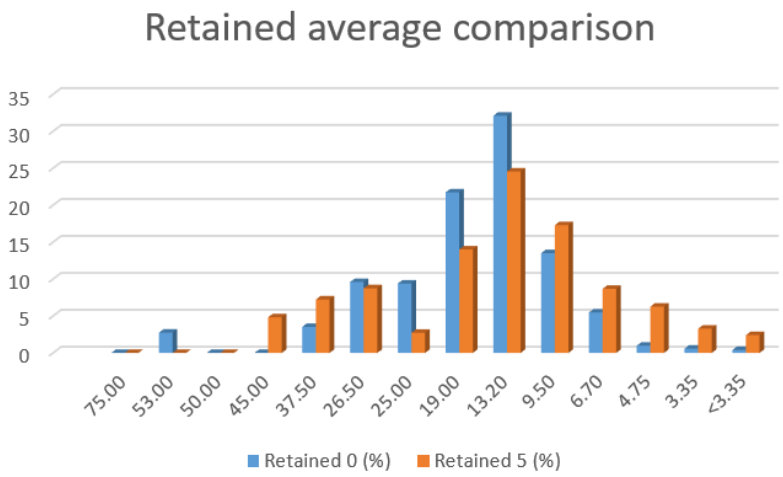


Figure 22 - Retained average comparison for a 10% outlier

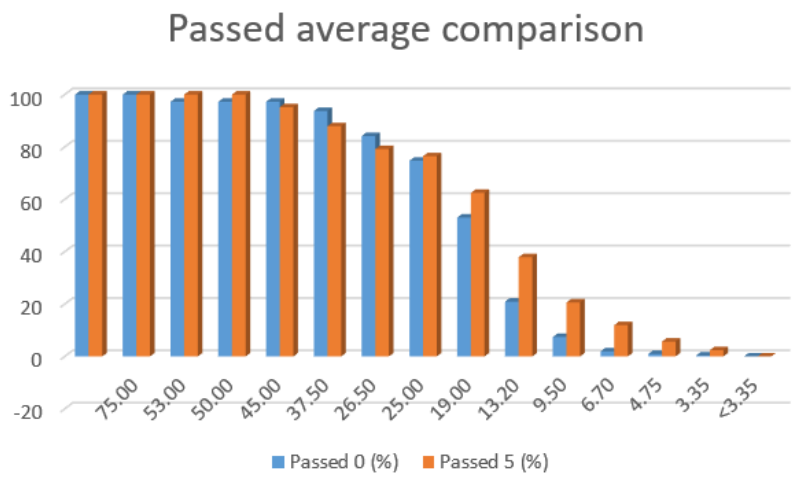


Figure 23 - Passed average comparison for a 10% outlier

A quick look to the previous average comparisons of the retained values figures, of the three outliers analysis and no outlier analysis is enough to detect a similarity in the shape of each parameter.

There is, however, a clear tendency on all analysis to have a lower value for 25,00mm, and a higher value for 26,50mm. There is also a lower discrepancy at the extreme sizes, both lower and higher. That discrepancy is then noted at 19,00 and 13,20mm, where the sieving values are higher than any of the analysis.

A closer look to the last two figures, representative of the retained and passed average comparisons for an outlier of 10% shows that the analysis has a high level of accuracy, with the one clear discrepancy being at 25,00m, as with any of the previous analysis.

4.4.1 Individual image analysis

The following figures are representative of the percentage difference between each image analysis values and the sieving values obtained. The rest of the figures related can be found on Appendix I.

4.4.1.1 Set number 3

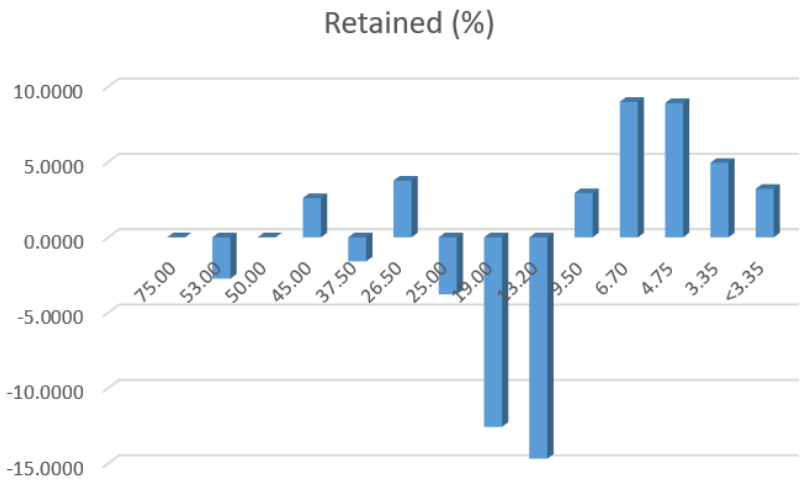


Figure 24 - Difference between sieving and set 3 image 1 retained percentage

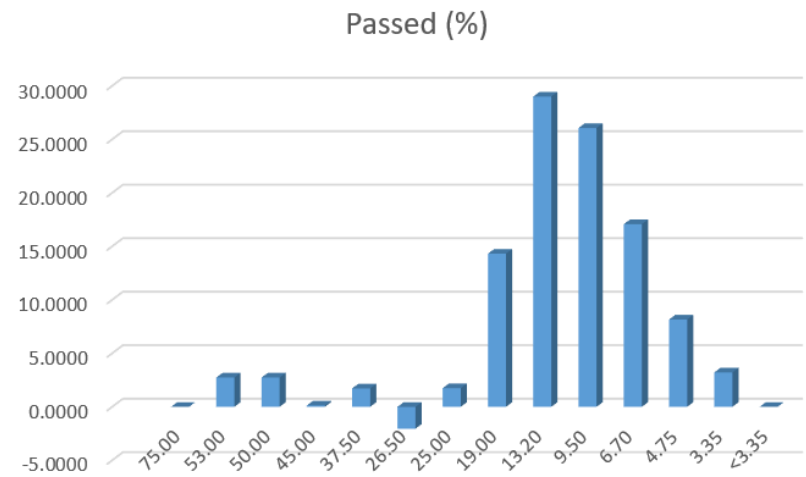


Figure 25 - Difference between sieving and set 3 image 1 passed percentage

4.4.1.2 Set number 4

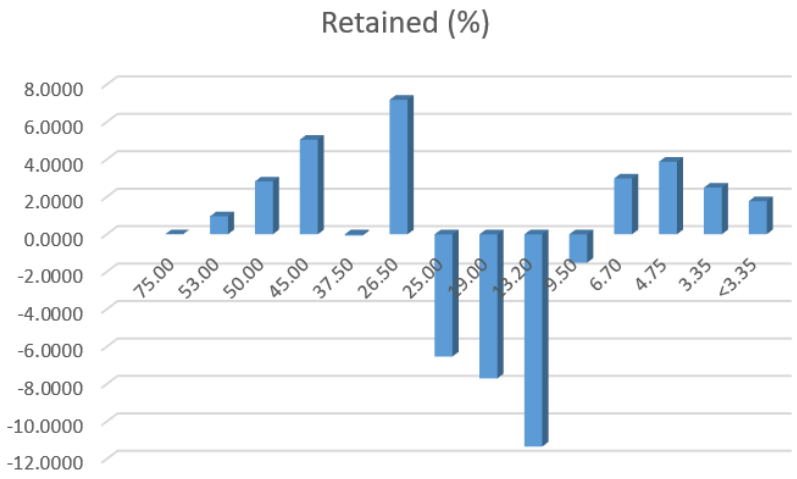


Figure 26 - Difference between sieving and set 4 image 1 retained percentage

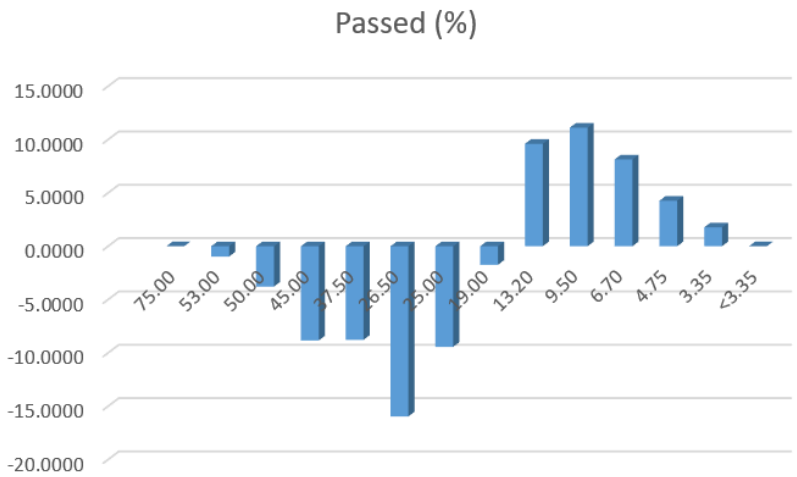


Figure 27 - Difference between sieving and set 4 image 1 passed percentage

4.4.1.3 Set number 5

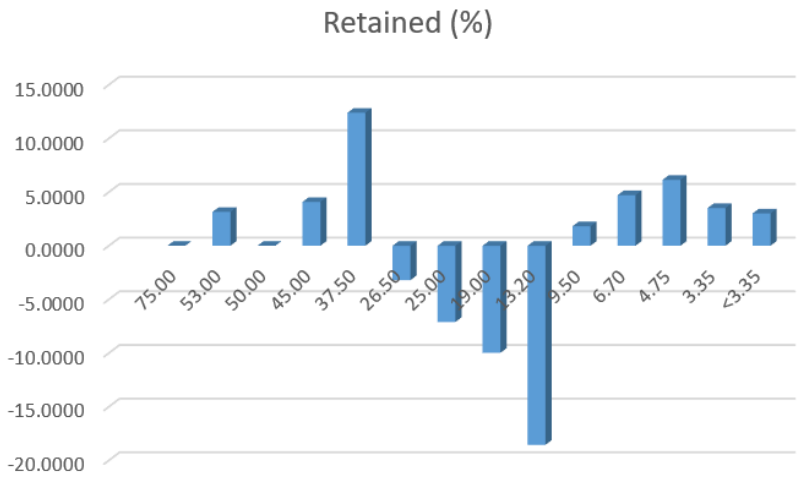


Figure 28 - Difference between sieving and set 5 image 1 retained percentage

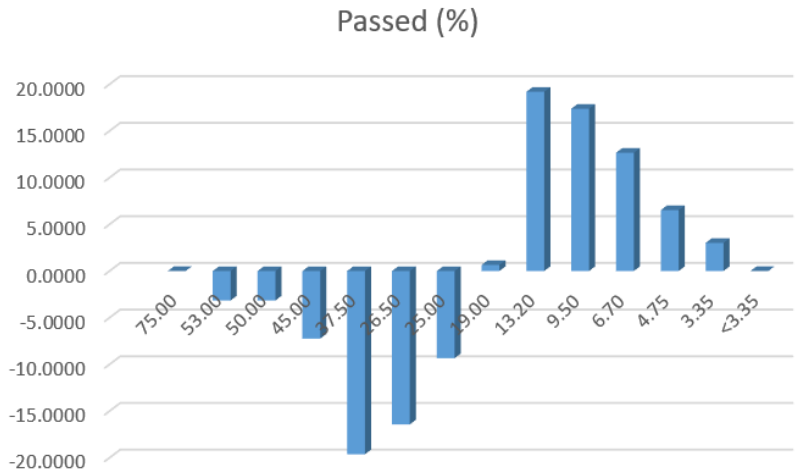


Figure 29 - Difference between sieving and set 5 image 1 passed percentage

4.4.1.4 Analysis

Looking at the previous figures provided for set number 3, 4 and 5, there is one clear common denominator. The images that provide a less accurate analysis of the material are the ones that lack the artificial lightning.

The results are also affected by the angle of the camera, but these are nowhere close to the difference seen between the analysis of images with and without the artificial lightning.

4.5 Granulometric curve analysis

In order to get a better understanding of the overall granulometric curves generated by the images analysis, as well as its level of similarity with the mechanical analysis, the granulometric curve of each image set was put together in an image, along with the granulometric curve of the mechanical analysis.

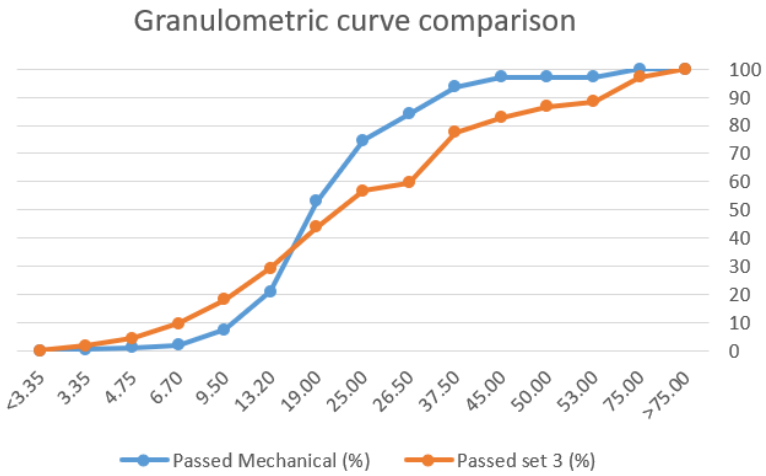


Figure 30 - Comparison between the granulometric curves of the mechanical sieving and set 3 analysis

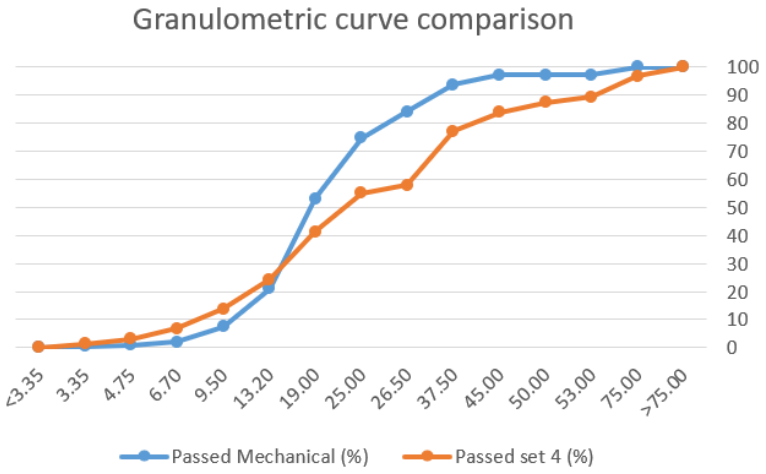


Figure 31 - Comparison between the granulometric curves of the mechanical sieving and set 4 analysis

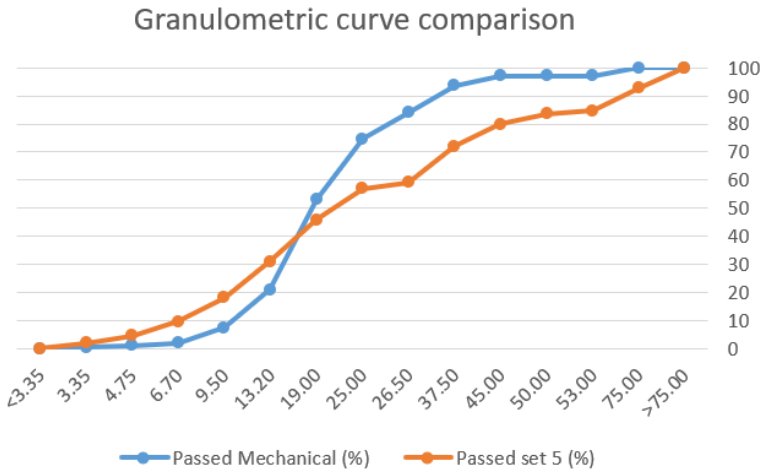


Figure 32 - Comparison between the granulometric curves of the mechanical sieving and set 5 analysis

A quick look at the previous three figures is enough to see some similarities between the three curves generated by the image analysis. One curious point is the crossing point between the image analysis curve and the mechanical curve, as in all three image analysis curve is between sizes 13,20 and 19,00mm. As such, there is also a clear tendency present in the image analysis, as a higher passed percentage is visible below size 13,20mm, and a lower passed percentage above size 19,00mm.

Another point that could be mentioned is a certain linear aspect to each image analysis curve, as well as a drop in every curve at value 26,50mm, however this could be explained by the fact that it has the lower interval difference for the higher values, leading to a certain uncertainty in its analysis.

Lastly, all three analysis also present higher passed percentage values after size 53,00m, leading to the expect final value of 100% passed for every curve, within the represented sizes.

Considering that the three represented sets, 3, 4 and 5, all have photographs without artificial lightning, an extra granulometric curve comparison was made, where only the photographs with artificial lightning was used.

For set number 3, the images analysis, with artificial lightning, considered were:

- 3 set _ 1
- 3 set _ 2
- 3 set _ 3
- 3 set _ 4
- 3 set _ 7
- 3 set _ 7 extrafullscan
- 3 set _ 9

For set number 4, the images analysis, with artificial lightning, considered were:

- 4 set _ 1
- 4 set _ 2
- 4 set _ 4
- 4 set _ 5
- 4 set _ 6
- 4 set _ 8
- 4 set _ 9
- 4 set _ 10
- 4 set _ 12

For set number 5, the images analysis, with artificial lightning, considered were:

- 5 set _ 2
- 5 set _ 4
- 5 set _ 5
- 5 set _ 8
- 5 set _ 9
- 5 set _ 11
- 5 set _ 12

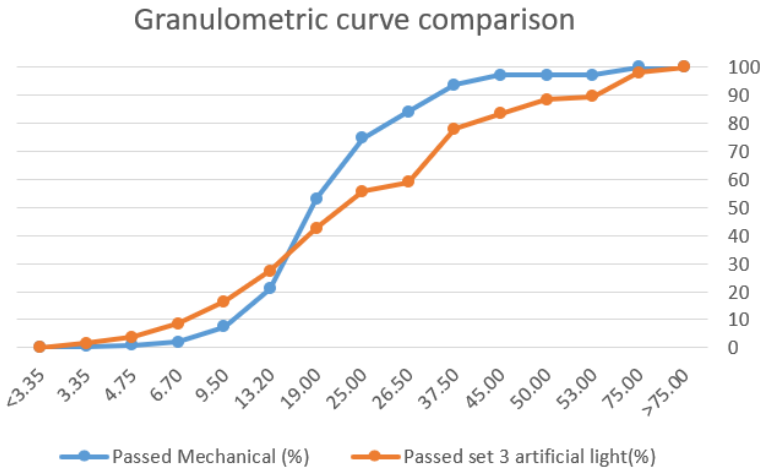


Figure 33 - Comparison between the granulometric curves of the mechanical sieving and set 3 analysis (artificial lightning)

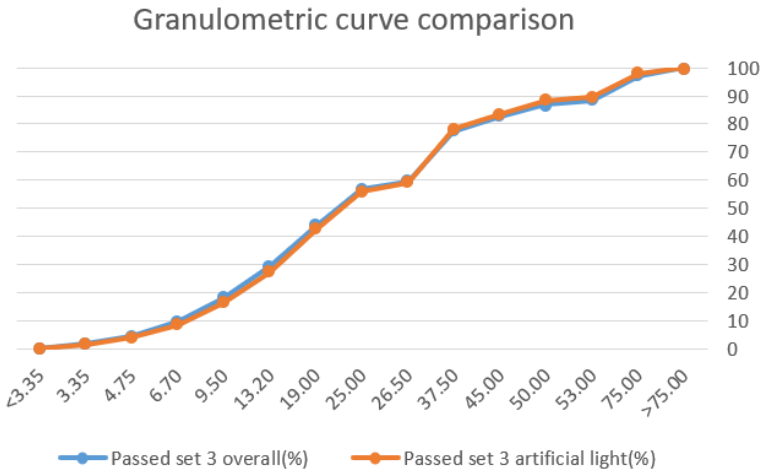


Figure 34 - Comparison between the granulometric curves of set 3 analysis and set 3 analysis (artificial lightning)

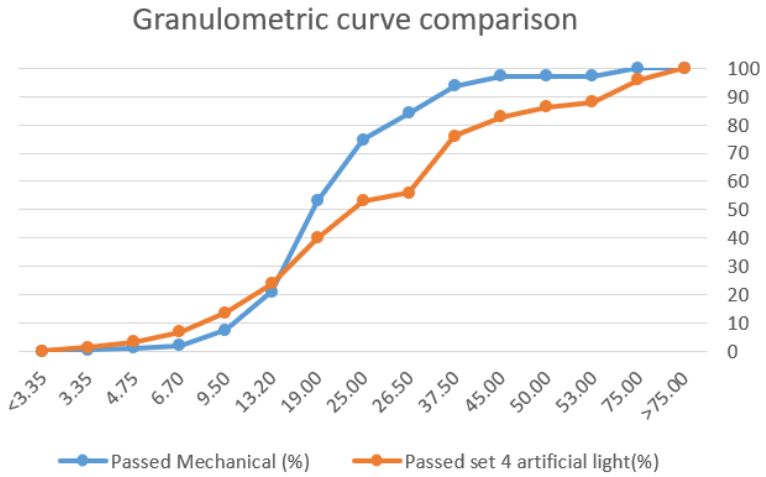


Figure 35 - Comparison between the granulometric curves of the mechanical sieving and set 4 analysis (artificial lightning)

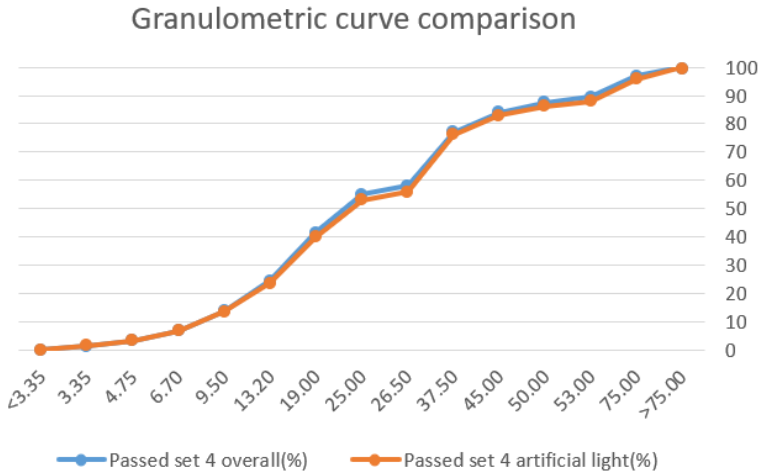


Figure 36 - Comparison between the granulometric curves of set 4 analysis and set 4 analysis (artificial lightning)

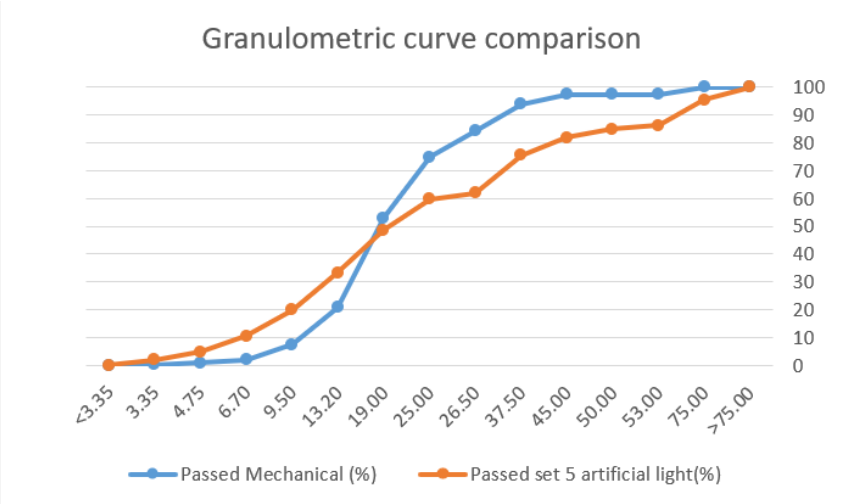


Figure 37 - Comparison between the granulometric curves of the mechanical sieving and set 5 analysis (artificial lightning)

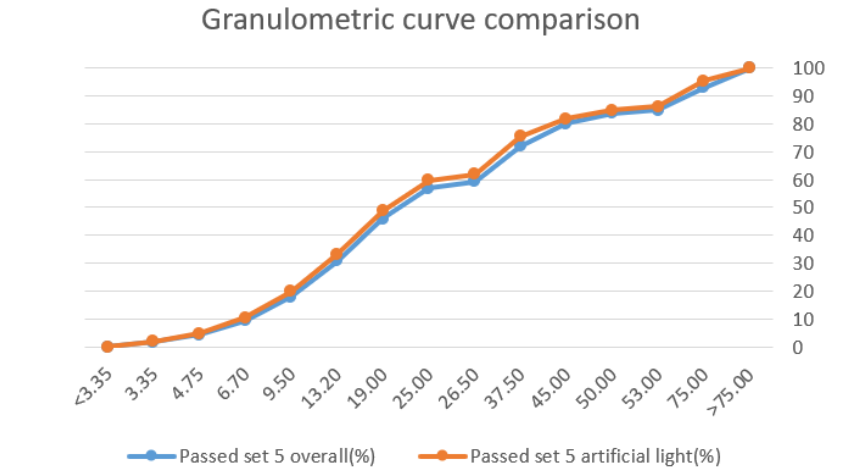


Figure 38 - Comparison between the granulometric curves of set 5 analysis and set 5 analysis (artificial lightning)

The figures that compare the mechanical analysis with the image with artificial lightning analysis do not show a considerable difference from the pictures that show a comparison between the mechanical analysis and the overall image analysis, as it was expected, considering the similarities between the retained values for both overall and artificial lightning photographs.

Regarding the figures that compare the overall image analysis with the image with artificial lightning analysis, there is a clear similarity between the curves, with the curves from set number 5 being the ones that have a higher disparity of values. Curiously, it is also on set number 5 that the artificial lightning curve

is above the overall curve.

One last interesting comparison to perform is between the overall image analysis for each set, the images with artificial lightning, and the images with natural light.

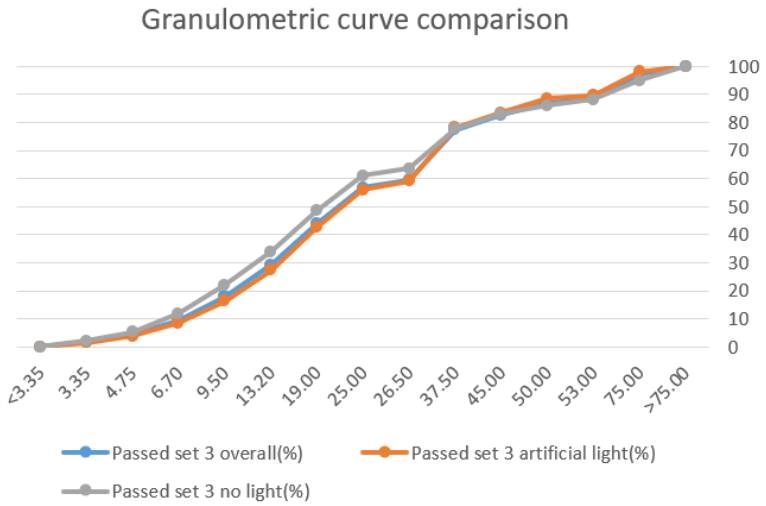


Figure 39 - Comparison between the granulometric curves of set 3 analysis, set 3 analysis (artificial lightning) and set 3 analysis (natural light)

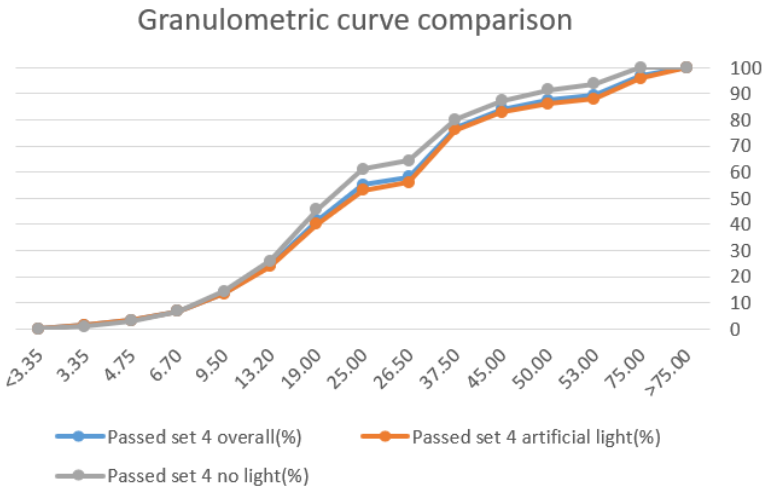


Figure 40 - Comparison between the granulometric curves of set 4 analysis, set 4 analysis (artificial lightning) and set 4 analysis (natural light)

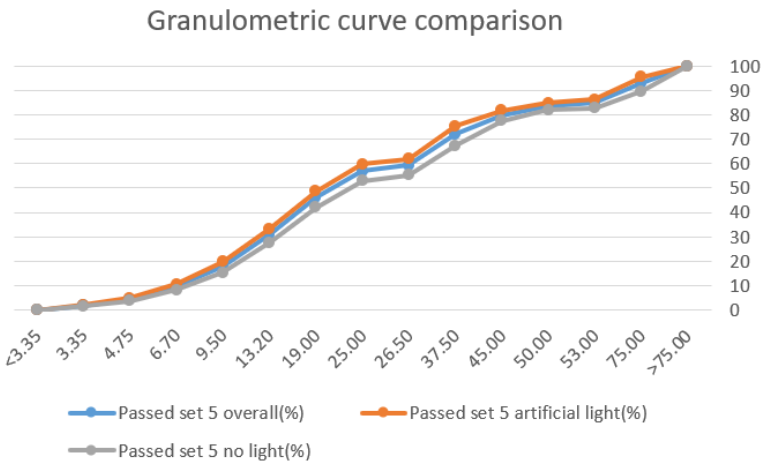


Figure 41 - Comparison between the granulometric curves of set 5 analysis, set 5 analysis (artificial lightning) and set 5 analysis (natural light)

Both sets number 3 and 4 have a tendency to for higher passed percentage values on the images with natural light, whereas set number 5 shows a lower passed percentage value for the images with natural light. Naturally, sets number 3 and 4 also show a tendency for lower values for passed percentage, and set number 5 a higher value for passed percentage. This was expected, as the overall analysis granulometric curve is situated in-between the natural light (no light) and the artificial light curves. Interestingly enough, there is no shape discrepancy between any of the curves, which leads to believe that the influence of the light is mostly relevant to the accuracy of the analysis.

4.5.1 Individual analysis

The following figures are representative of the comparison between the granulometric curves of the mechanical sieving and each image analysis.

4.5.1.1 Set number 3

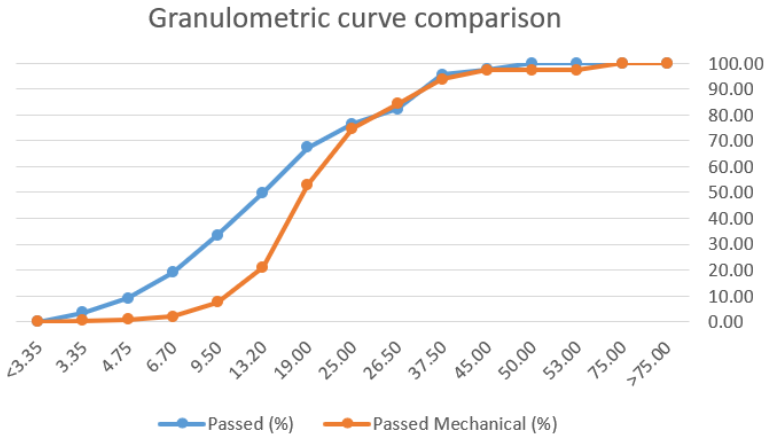


Figure 42 - Comparison between the granulometric curves of the mechanical sieving and set 3 image 1 analysis

4.5.1.2 Set number 4

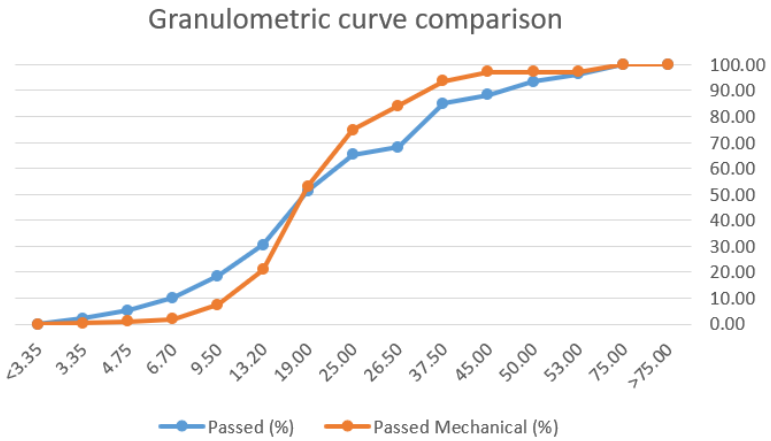


Figure 43 - Comparison between the granulometric curves of the mechanical sieving and set 4 image 1 analysis

4.5.1.3 Set number 5

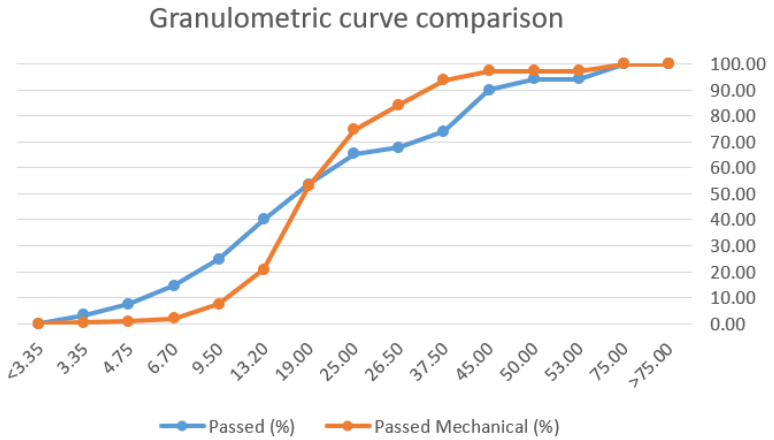


Figure 44 - Comparison between the granulometric curves of the mechanical sieving and set 5 image 1 analysis

4.5.1.4 Analysis

Possibly the most noteworthy aspect of every of the previous figures, regarding the comparison between mechanical sieving and each of the image analysis, is the same noticeable low increment to the passed percentage at the size of 26,50mm. This continuous, and very visible, detail, appears to be a strong indicator that WipFrag might have a deficiency regarding the estimation of particle size when the difference between the previous size and the current is not considerable, at higher sizes, such is the case with the seen 25,00 and 26,50mm values displayed in the forementioned figures.

Another aspect worthy of mention is the similarity noticed between the curves of the mechanical analysis and the image analysis, in most figures, as well as a similar crossing point between the curves in the figures.

However, there are also some figures that are very much different in its curves. This event is mostly seen with the comparison made for:

- Set number 4 image 10
- Set number 5 image 3

- Set number 5 image 5
- Set number 5 image 7

Nonetheless, despite the different curve aspect, all of the previously mentioned images also have one other detail in common, which is the incredible similarity with the mechanical analysis curve up until the size of 13,20mm. It is only at 13,20mm that the curve gains a totally different shape. Considering only image number 3 and 5 of set number 5 were based on photographs with natural light, it is safe to say that the difference is not due to the presence of artificial lightning, as half of the mentioned images were based on artificial lightning, and the other half with natural lightning.

5. Discussion

After analyzing and comparing the results obtained, it is possible to conclude that:

- The photograph conditions present a strong influence to the analysis outcome, therefore being an important factor to have in mind when performing optical analysis;
- WipFrag image analysis is very sensitive to lightning conditions;
- It is important to have the best photograph possible to have an accurate analysis, meaning less material that does not belong to the lot that is meant to be analyzed, such as floor, tables, metals, et cetera, that will affect the automatic filters;
- Depending on the goal of the analysis, it is possible to manually filter images. However, this should only be applied when necessary to control the current size distribution, or where it will not affect the production, as it is a task that consumes a lot of time;
- WipFrag is a potent and useful tool, simple to use, whilst capable of complex possibilities;
- Sampling bias was an unavoidable issue that was always present during trials, resulting in a lower accuracy;
- Finally, the results obtained were very satisfactory, and the accuracy is as expected.

While there are many factors to take into consideration when opting for an optical analysis system, there are also some very clear advantages, and disadvantages.

From the study of the analysis performed during this dissertation, the most important conclusion that was reached was the inaccuracy, even if ever so slightly, present in every image analysis.

Due to this inaccuracy, the suggestion is to use the optical analysis software to control the classification processes, or any other process that requires size management, but not depend on it. In other words, if it is a very strict circuit that needs to maintain an extremely rigorous size control, the use of optical analysis, while cheaper, might not be the best ideia.

However, if the control is not very rigorous, or even if it is mostly for an overall ideia of the classification, or fragmentation, output, it is a very cost-effective solution that should be considered.

6. Final considerations

In regard to the software, WipFrag, it is possible to reach a few conclusions:

- It is an incredibly powerful tool, not only for the mining industry, but for the explosives and material handling industries as well;
- Its portability, as it is available for iOS devices, is an extraordinary feat, that allows for an even faster analysis;
- The UI is very simple and easy to grasp, allowing new users to get right to work without much need for an advanced tutorial;
- The filter options are very useful and intuitive;
- When paired with the proper control technlogy and system, it is a must have tool for a better control of the material.

In regard to the initial proposal, it can be said that:

- The initial goal was reached, as not only was it possible to analyze a variety of images with WipFrag, it was also possible to reach results that were considered accurate;
- The issues found along the work were considered useful in a way that allowed not only a better understanding of the software, but also a better understanding of how certain parameters influence the outcome of the analysis.

7. Future research prospect

Despite the conclusion of this dissertation, further research on the matter would be extremely interesting.

This further research would revolve around more data gathered, which means a bigger sample base.

A few other factors that could be studied are:

- Type of material;
- Environmental conditions;
- Image parameters.

Researching the results of optical analysis over different types of material would be very interesting. It would allow a better understanding of how the software, in this case WipFrag, analysis each material, and how accurate it would be for each type of material.

The effect of environmental conditions would also be a very interesting study object. Ranging from lightning conditions to water from rain, it would interesting to see how a small chance in lightning would influence the results, and from there apply small increments and analyse the results. The presence of water, considering the possibility of rain, and other water sources, would also be interesting, in the same way as the lightning, as it would allow a study of its influence on the software analysis.

Finally, the image parameters, which would range from camera quality, overall settings, such as contrast, blur and threshold, et cetera. These would also be quite an interesting study subject, as all are, most likely, an influence over the software analysis.

8. Literature and software

8.1 Books and articles

Fragmentação e Classificação de Rochas e Minérios - *Mário Rui Machado Leite*

Automated Online Optical Sizing Analysis - *Norbert H. Maerz*

Optical sizing analysis of blasted rock: lessons learned - *Norbert H. Maerz, Tom C. Palangio, Thomas W. Palangio and K. Elsey*

WipFrag Image Based Granulometry System - *Norbert H. Maerz, Tom C. Palangio and John A. Franklin*

Limestone Rock Fragmentation Analysis Using WipFrag - *M. Venkatesh*

2D image analysis using WipFrag software compared with actual sieving data of Kiruna magnetite loaded from a drawpoint - *Matthias Wimmer and Finn Ouchterlony*

Case studies using the WipFrag image analysis system - *Norbert H. Maerz*

Aggregate Sizing and Shape Determination Using Digital Image Processing - *Norbert H. Maerz*

A Blind Comparison Between Results of Four Image Analysis Systems Using a Photo-Library of Piles of Sieved Fragments - *John-Paul Latham, John Kemeny, Norbert H. Maerz, Michael Noy, Jacques Schleifer and Simon Tose*

Evaluation of Optical Sizing Methods - *Tom Barkley and Jack Eloranta*

Advanced automatic optical blast fragmentation sizing and tracking - *Thomas W. Palangio, Tom C. Palangio and Norbert H. Maerz*

Optical digital fragmentation measuring systems – inherent sources of error - *Norbert H. Maerz and Wei Zhou*

8.2 Websites

https://www.mclanahan.com/processes/sizing-screening - 08/07/2018

https://www.gsmarena.com/oneplus_3-7995.php - 20/07/2018

https://www.androidcentral.com/oneplus-3-specs - 20/07/2018

8.3 Software

Wipfrag - http://wipware.com/products/wipfrag/

Microsoft Excel - https://products.office.com/en/excel

Microsoft Word - https://products.office.com/en/word

Notepad++ - https://notepad-plus-plus.org/

Leanpub - https://leanpub.com/

Dropbox - https://www.dropbox.com/

Citation Machine - http://www.citationmachine.net/

Zotero - https://www.zotero.org/

ResearchGate - https://www.researchgate.net

List of Figures

List of Tables

List of Terms and Acronyms

cm - Centimeter

COREM - Organization in Canada devoted to mineral processing R/D

FEUP - Faculdade de Engenharia da Universidade do Porto

GIS - Geographic Information System

GPS - Global Positioning System

IMX - Image sensor

iOS - Mobile operating system developed by Apple

KCO - Kuznetsov-Cunningham-Ouchterlony

kg - Kilogram

PDAF - Phase Detection Auto Focus

PDF - Portable Document Format

mm - Millimeter

MP - Megapixel

OIS - Optical Image Stabilization

OLE - Object Linking and Embedding

OPC - OLE for Process Control

R/D - Research and Development

TTL - Transistor-Transistor Logic

UAV - Unmanned Aerial Vehicle

UI - User Interface

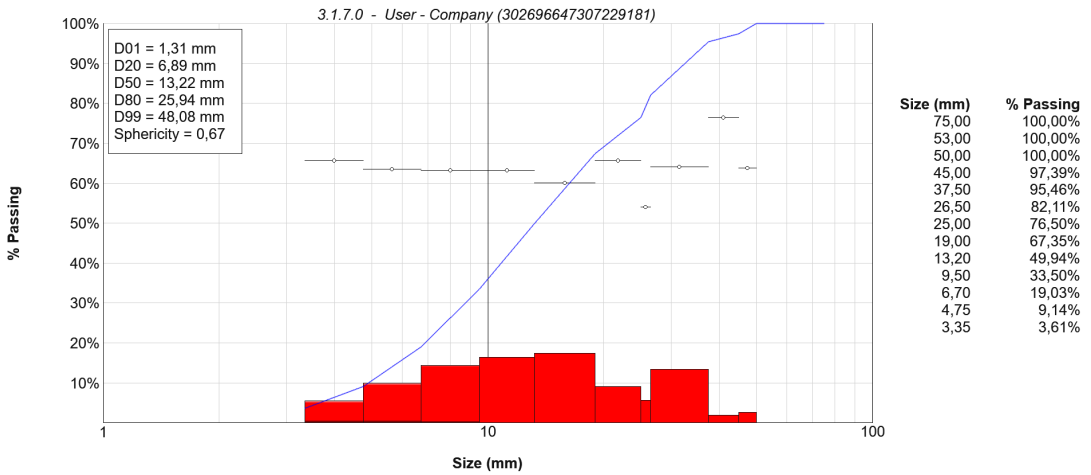
USD - United States Dollar

Âµm - Micrometer

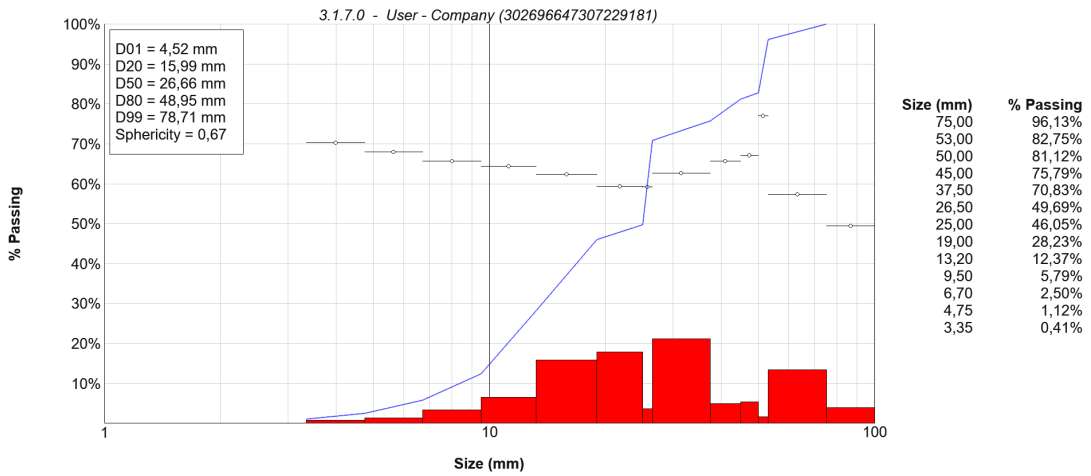
Appendix I

WipFrag results

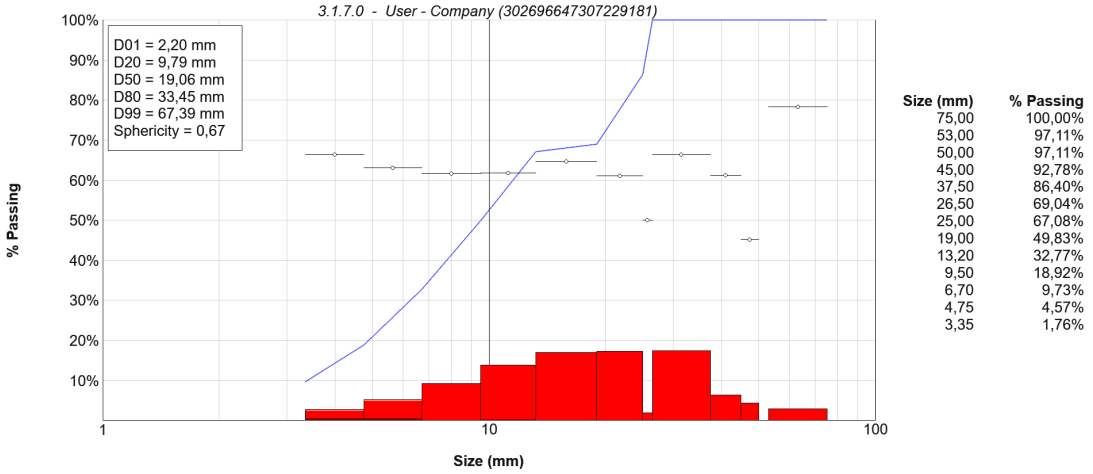
Set number 3



Results set 3 image 1

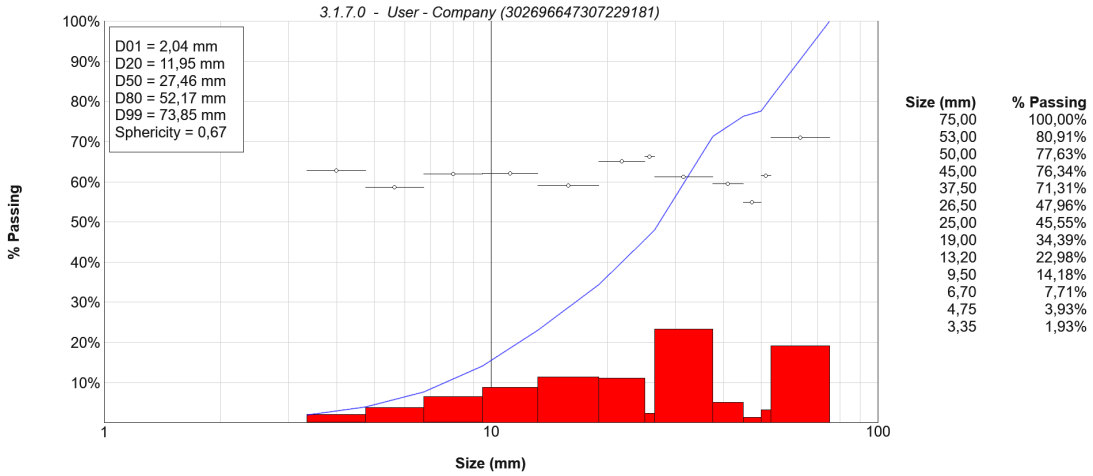


Results set 3 image 2



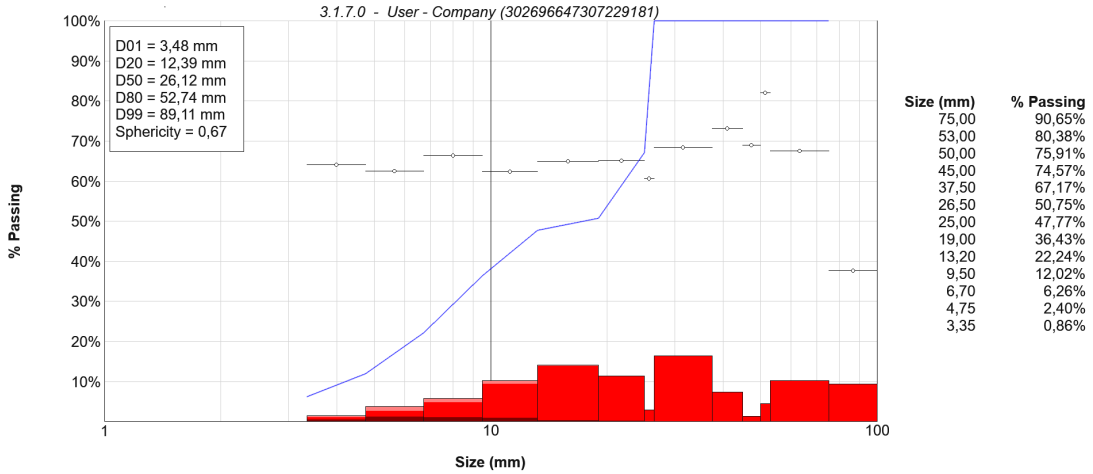
Size (mm)	% Passing
75,00	100,00%
53,00	97,11%
50,00	97,11%
45,00	92,78%
37,50	86,40%
26,50	69,04%
25,00	67,08%
19,00	49,83%
13,20	32,77%
9,50	18,92%
6,70	9,73%
4,75	4,57%
3,35	1,76%

Results set 3 image 3



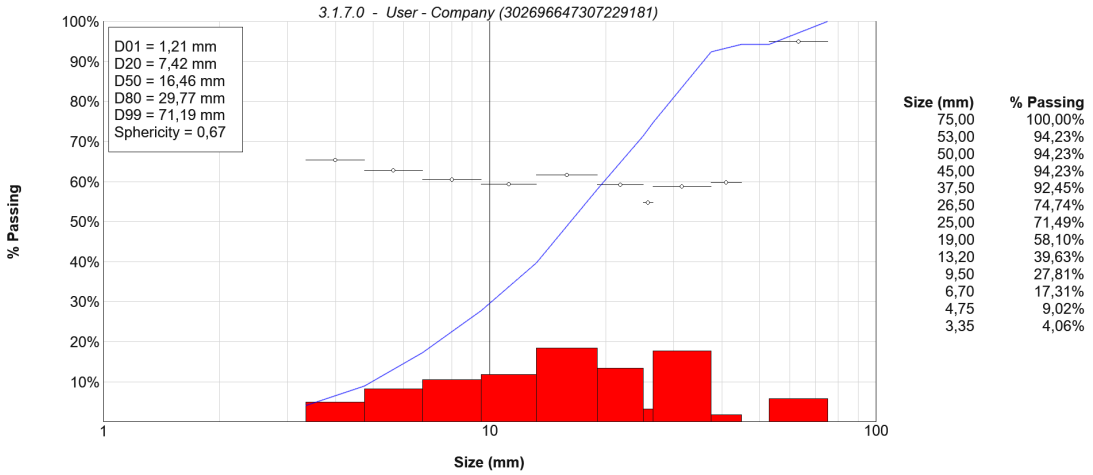
Size (mm)	% Passing
75,00	100,00%
53,00	80,91%
50,00	77,63%
45,00	76,34%
37,50	71,31%
26,50	47,96%
25,00	45,55%
19,00	34,39%
13,20	22,98%
9,50	14,18%
6,70	7,71%
4,75	3,93%
3,35	1,93%

Results set 3 image 4



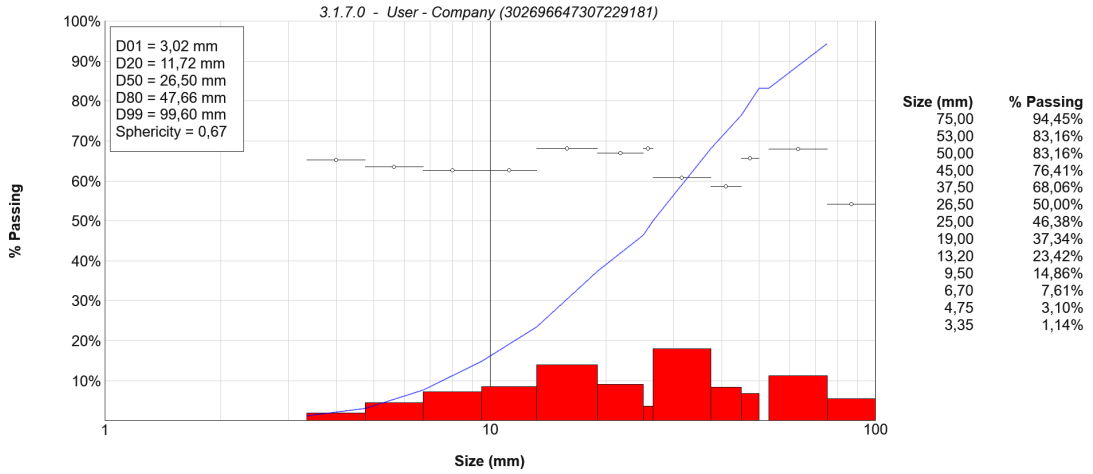
Size (mm)	% Passing
75,00	90,65%
53,00	80,38%
50,00	75,91%
45,00	74,57%
37,50	67,17%
26,50	50,75%
25,00	47,77%
19,00	36,43%
13,20	22,24%
9,50	12,02%
6,70	6,26%
4,75	2,40%
3,35	0,86%

Results set 3 image 5



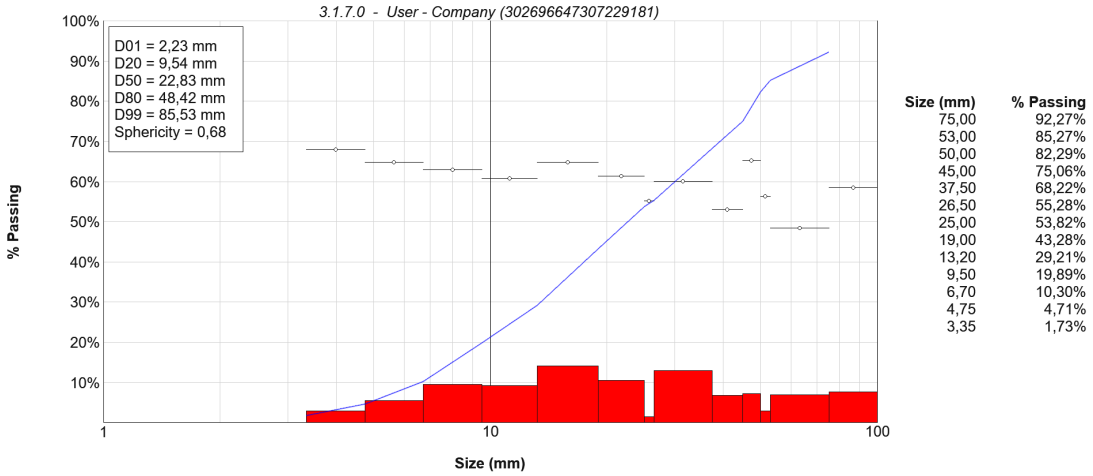
Size (mm)	% Passing
75,00	100,00%
53,00	94,23%
50,00	94,23%
45,00	94,23%
37,50	92,45%
26,50	74,74%
25,00	71,49%
19,00	58,10%
13,20	39,63%
9,50	27,81%
6,70	17,31%
4,75	9,02%
3,35	4,06%

Results set 3 image 6



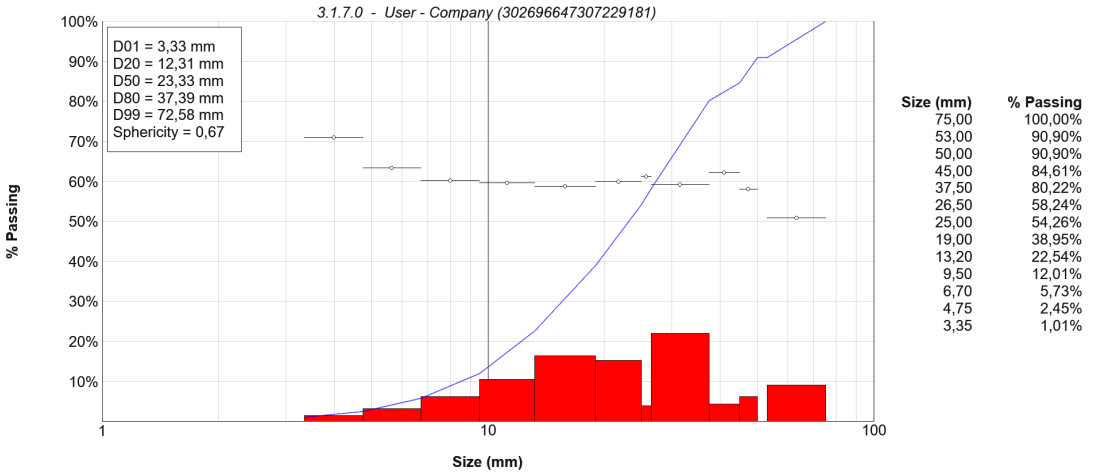
Size (mm)	% Passing
75,00	94,45%
53,00	83,16%
50,00	83,16%
45,00	76,41%
37,50	68,06%
26,50	50,00%
25,00	46,38%
19,00	37,34%
13,20	23,42%
9,50	14,86%
6,70	7,61%
4,75	3,10%
3,35	1,14%

Results set 3 image 7



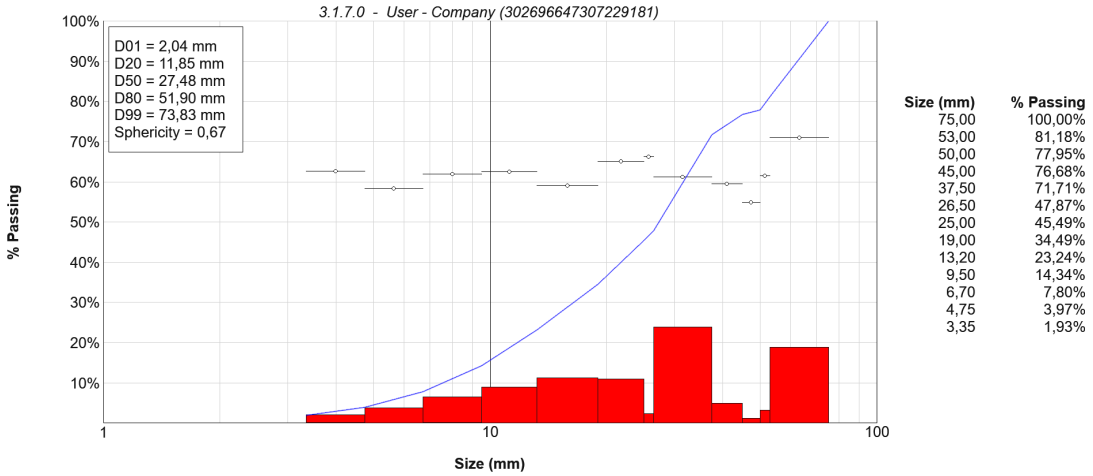
Size (mm)	% Passing
75,00	92,27%
53,00	85,27%
50,00	82,29%
45,00	75,06%
37,50	68,22%
26,50	55,28%
25,00	53,82%
19,00	43,28%
13,20	29,21%
9,50	19,89%
6,70	10,30%
4,75	4,71%
3,35	1,73%

Results set 3 image 8

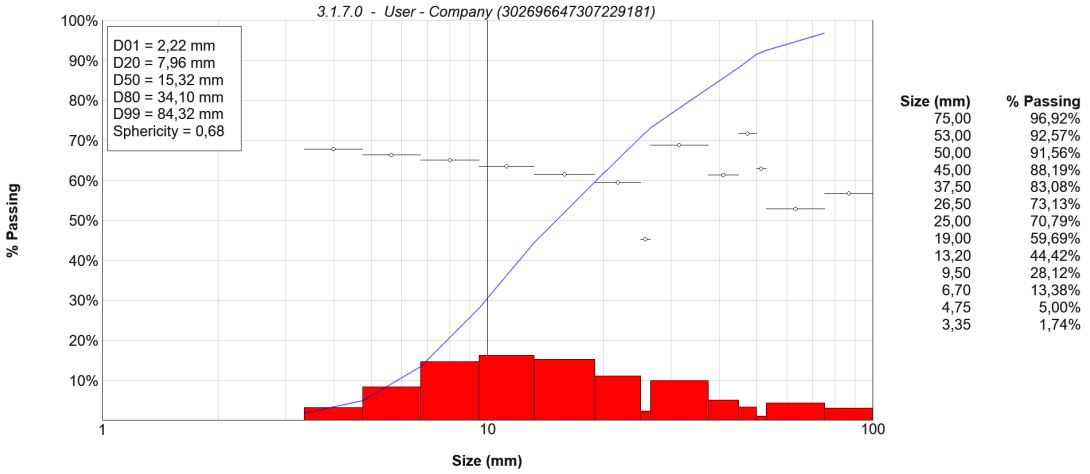


Results set 3 image 9

The two extra analysis performed for set number 3 were on image 4 and image 8:



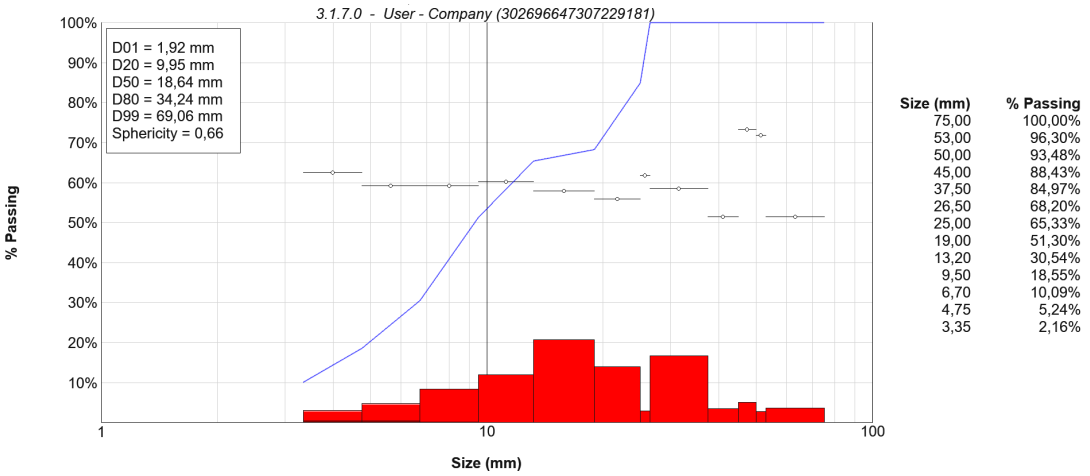
Results set 3 image 4, “Best Fit - Standard”



Size (mm)	% Passing
75,00	96,92%
53,00	92,57%
50,00	91,56%
45,00	88,19%
37,50	83,08%
26,50	73,13%
25,00	70,79%
19,00	59,69%
13,20	44,42%
9,50	28,12%
6,70	13,38%
4,75	5,00%
3,35	1,74%

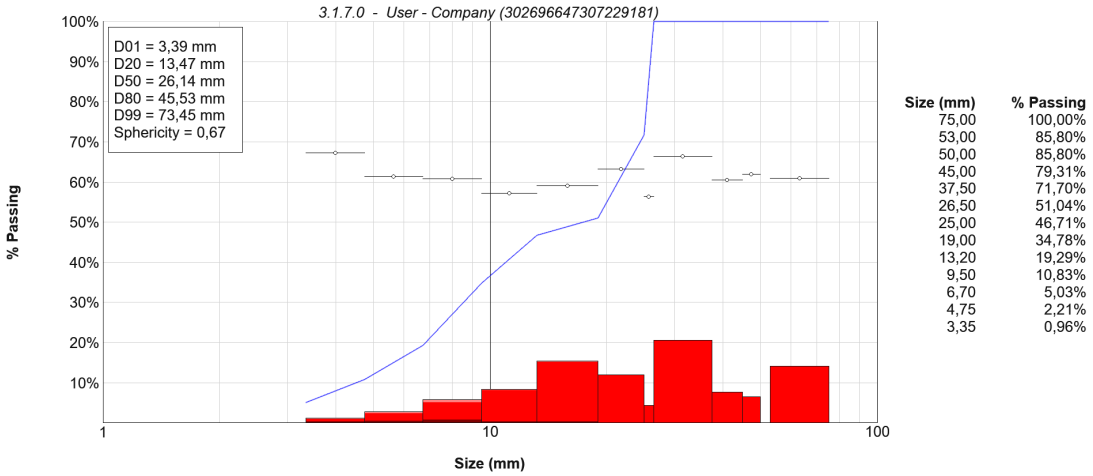
Results set 3 image 8, “Best Fit - Thorough”

Set number 4



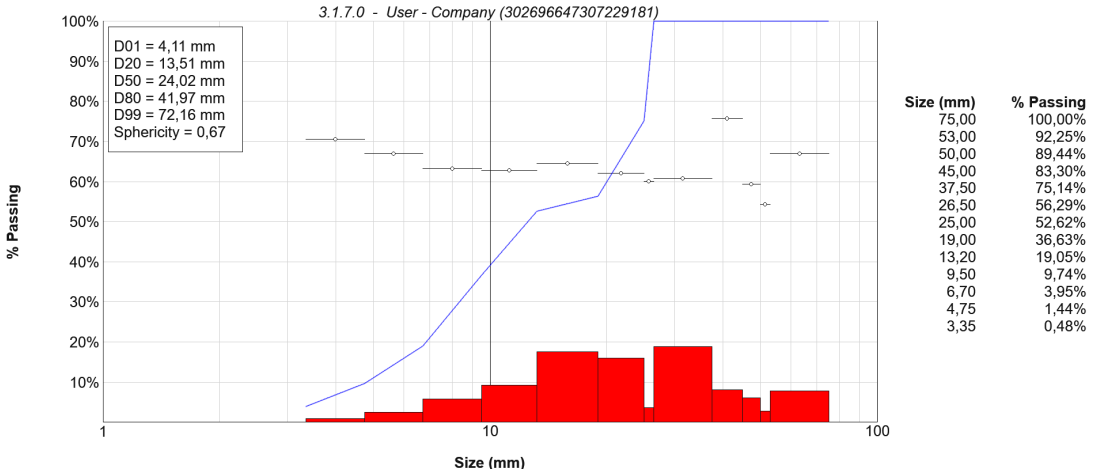
Size (mm)	% Passing
75,00	100,00%
53,00	96,30%
50,00	93,48%
45,00	88,43%
37,50	84,97%
26,50	68,20%
25,00	65,33%
19,00	51,30%
13,20	30,54%
9,50	18,55%
6,70	10,09%
4,75	5,24%
3,35	2,16%

Results set 4 image 1



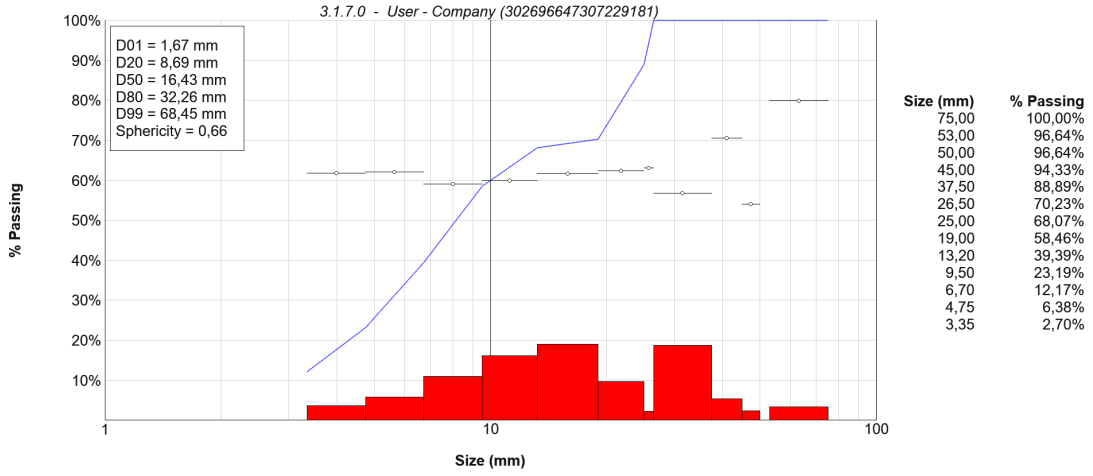
Size (mm)	% Passing
75,00	100,00%
53,00	85,80%
50,00	85,80%
45,00	79,31%
37,50	71,70%
26,50	51,04%
25,00	46,71%
19,00	34,78%
13,20	19,29%
9,50	10,83%
6,70	5,03%
4,75	2,21%
3,35	0,96%

Results set 4 image 2



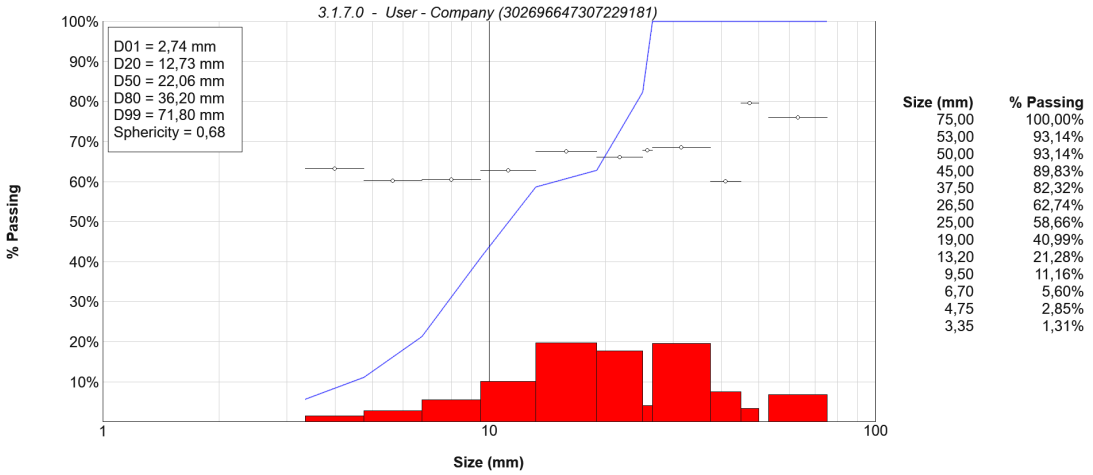
Size (mm)	% Passing
75,00	100,00%
53,00	92,25%
50,00	89,44%
45,00	83,30%
37,50	75,14%
26,50	56,29%
25,00	52,62%
19,00	36,63%
13,20	19,05%
9,50	9,74%
6,70	3,95%
4,75	1,44%
3,35	0,48%

Results set 4 image 3



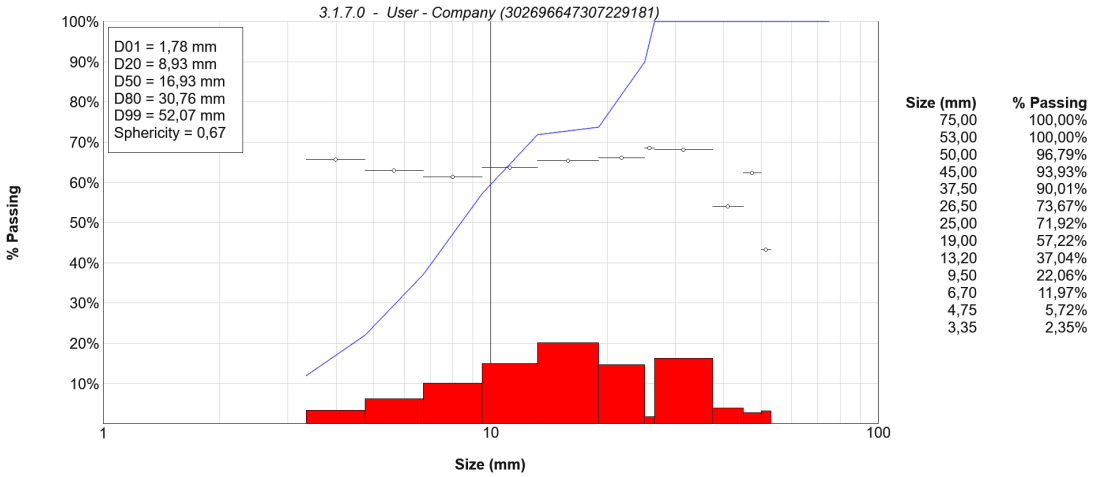
Size (mm)	% Passing
75,00	100,00%
53,00	96,64%
50,00	96,64%
45,00	94,33%
37,50	88,89%
26,50	70,23%
25,00	68,07%
19,00	58,46%
13,20	39,39%
9,50	23,19%
6,70	12,17%
4,75	6,38%
3,35	2,70%

Results set 4 image 4



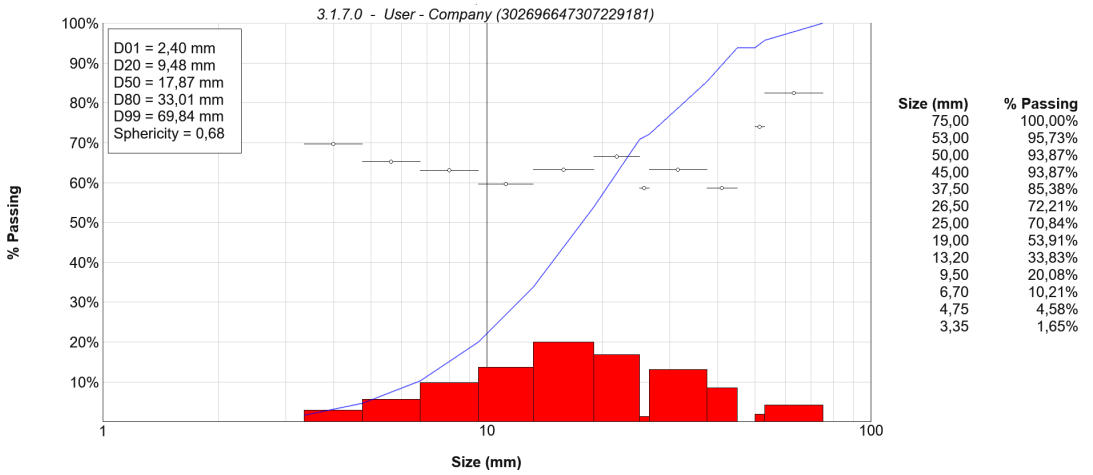
Size (mm)	% Passing
75,00	100,00%
53,00	93,14%
50,00	93,14%
45,00	89,83%
37,50	82,32%
26,50	62,74%
25,00	58,66%
19,00	40,99%
13,20	21,28%
9,50	11,16%
6,70	5,60%
4,75	2,85%
3,35	1,31%

Results set 4 image 5



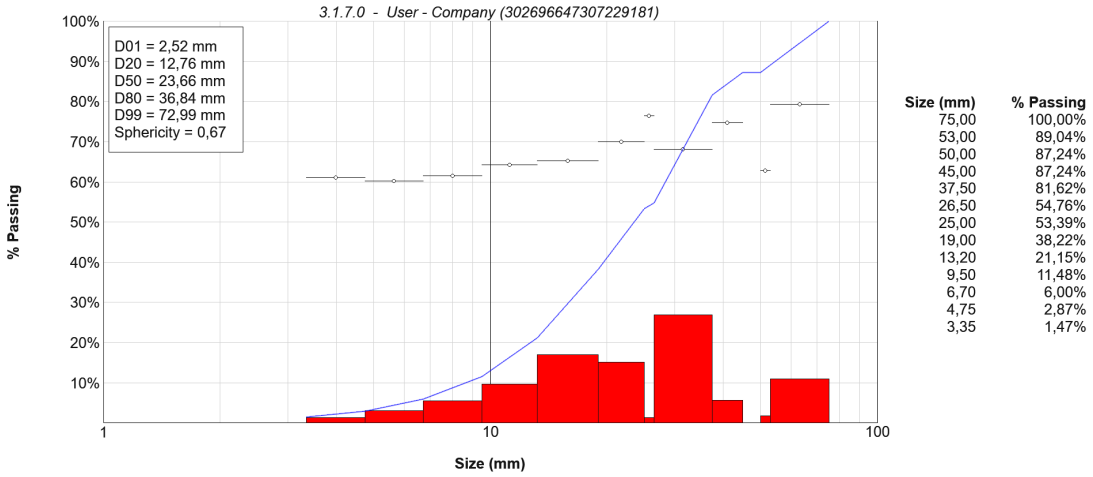
Size (mm)	% Passing
75,00	100,00%
53,00	100,00%
50,00	96,79%
45,00	93,93%
37,50	90,01%
26,50	73,67%
25,00	71,92%
19,00	57,22%
13,20	37,04%
9,50	22,06%
6,70	11,97%
4,75	5,72%
3,35	2,35%

Results set 4 image 6



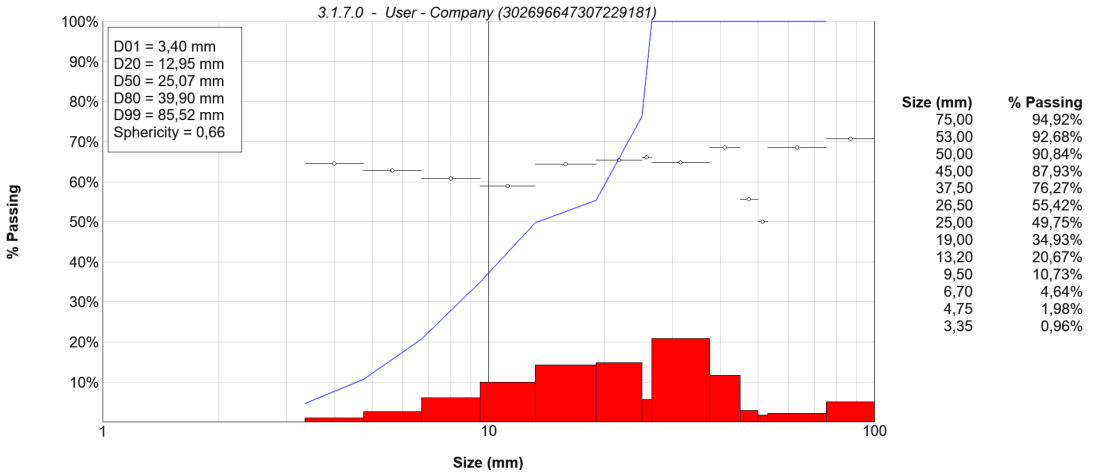
Size (mm)	% Passing
75,00	100,00%
53,00	95,73%
50,00	93,87%
45,00	93,87%
37,50	85,38%
26,50	72,21%
25,00	70,84%
19,00	53,91%
13,20	33,83%
9,50	20,08%
6,70	10,21%
4,75	4,58%
3,35	1,65%

Results set 4 image 7



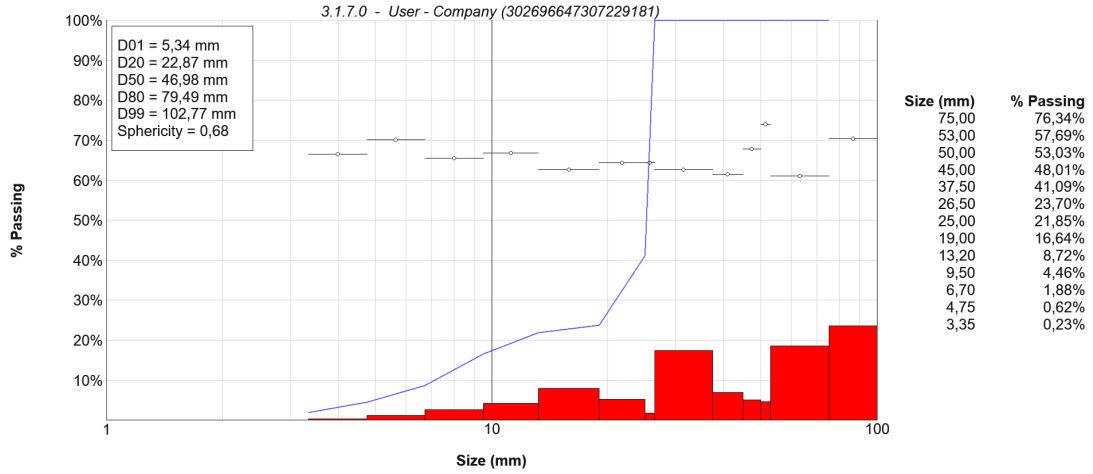
Size (mm)	% Passing
75,00	100,00%
53,00	89,04%
50,00	87,24%
45,00	87,24%
37,50	81,62%
26,50	54,76%
25,00	53,39%
19,00	38,22%
13,20	21,15%
9,50	11,48%
6,70	6,00%
4,75	2,87%
3,35	1,47%

Results set 4 image 8



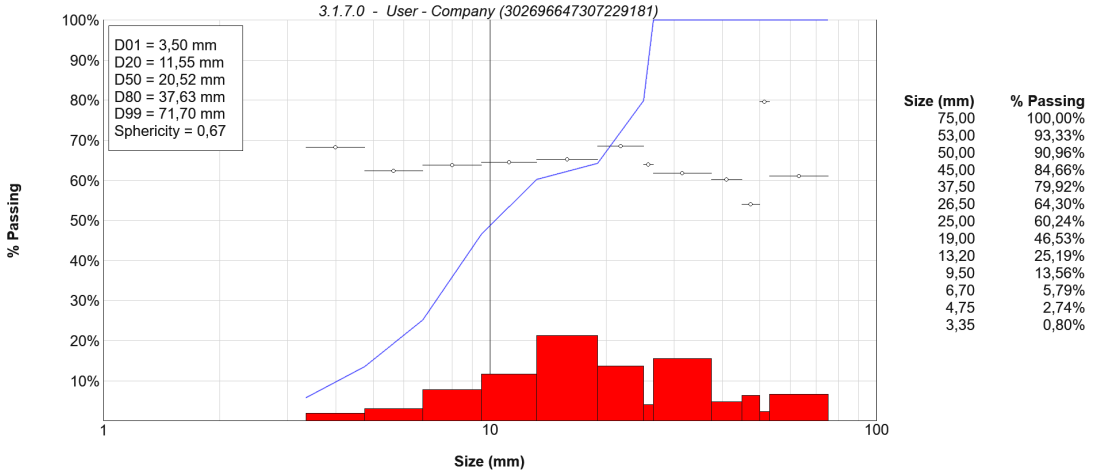
Size (mm)	% Passing
75,00	94,92%
53,00	92,68%
50,00	90,84%
45,00	87,93%
37,50	76,27%
26,50	55,42%
25,00	49,75%
19,00	34,93%
13,20	20,67%
9,50	10,73%
6,70	4,64%
4,75	1,98%
3,35	0,96%

Results set 4 image 9



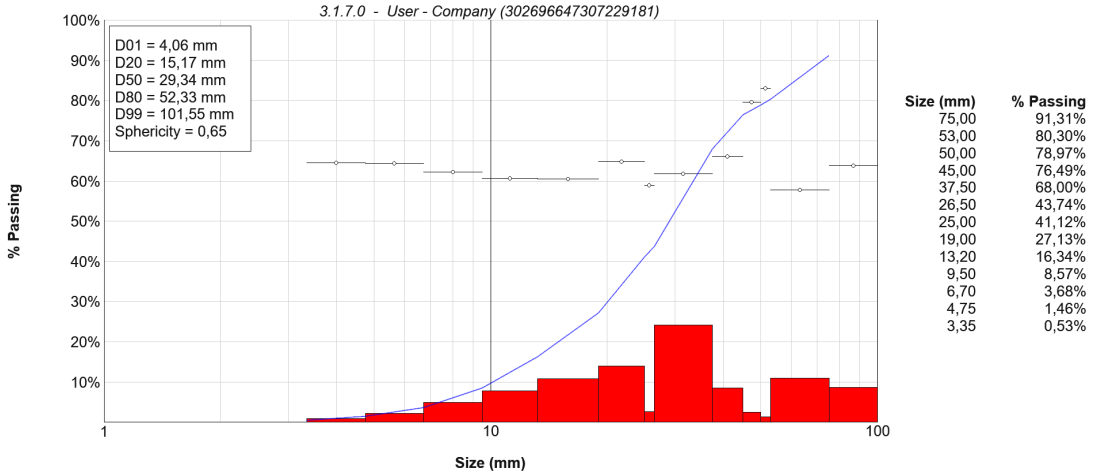
Size (mm)	% Passing
75,00	76,34%
53,00	57,69%
50,00	53,03%
45,00	48,01%
37,50	41,09%
26,50	23,70%
25,00	21,85%
19,00	16,64%
13,20	8,72%
9,50	4,46%
6,70	1,88%
4,75	0,62%
3,35	0,23%

Results set 4 image 10



Size (mm)	% Passing
75,00	100,00%
53,00	93,33%
50,00	90,96%
45,00	84,66%
37,50	79,92%
26,50	64,30%
25,00	60,24%
19,00	46,53%
13,20	25,19%
9,50	13,56%
6,70	5,79%
4,75	2,74%
3,35	0,80%

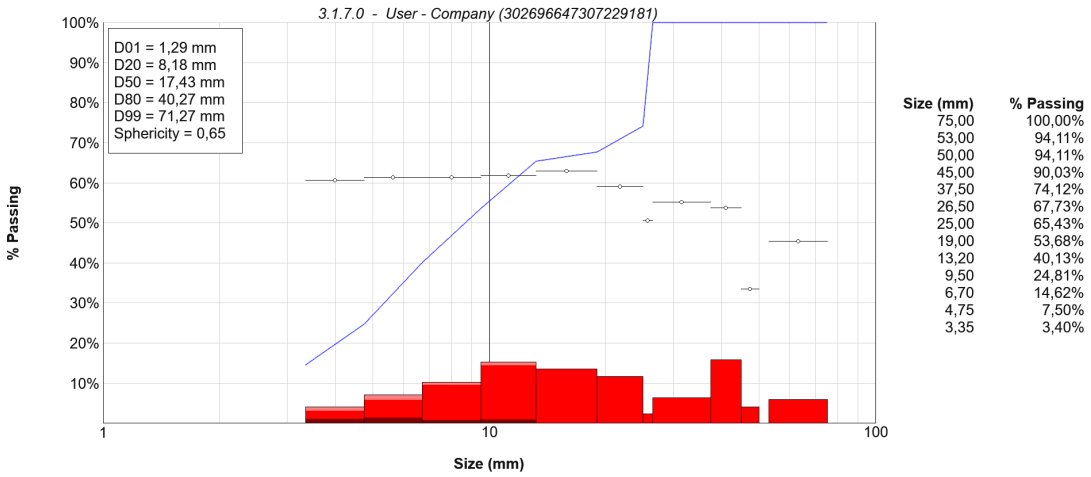
Results set 4 image 11



Size (mm)	% Passing
75,00	91,31%
53,00	80,30%
50,00	78,97%
45,00	76,49%
37,50	68,00%
26,50	43,74%
25,00	41,12%
19,00	27,13%
13,20	16,34%
9,50	8,57%
6,70	3,68%
4,75	1,46%
3,35	0,53%

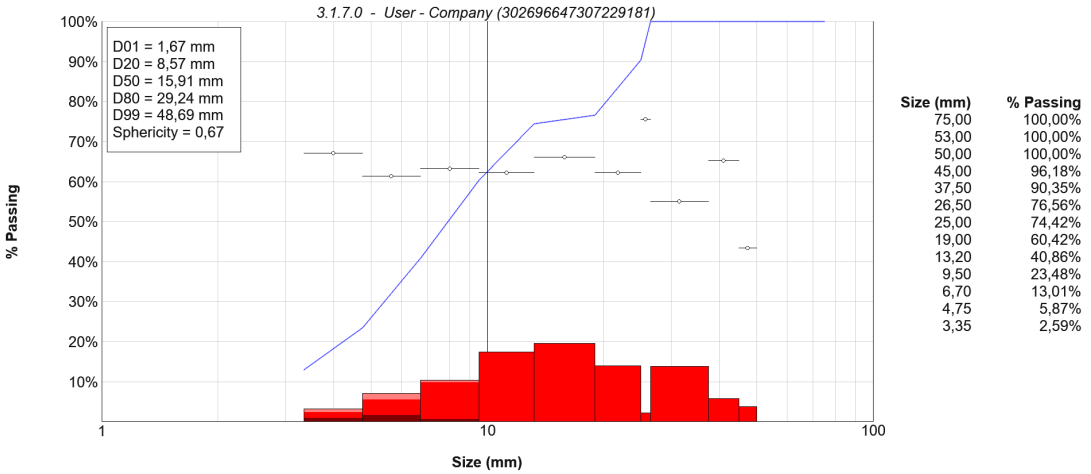
Results set 4 image 12

Set number 5



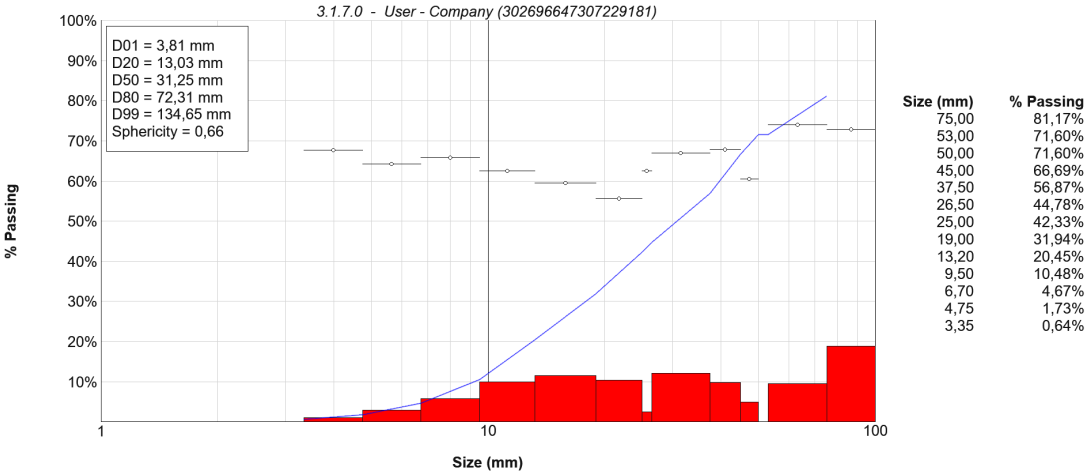
Size (mm)	% Passing
75,00	100,00%
53,00	94,11%
50,00	94,11%
45,00	90,03%
37,50	74,12%
26,50	67,73%
25,00	65,43%
19,00	53,68%
13,20	40,13%
9,50	24,81%
6,70	14,62%
4,75	7,50%
3,35	3,40%

Results set 5 image 1



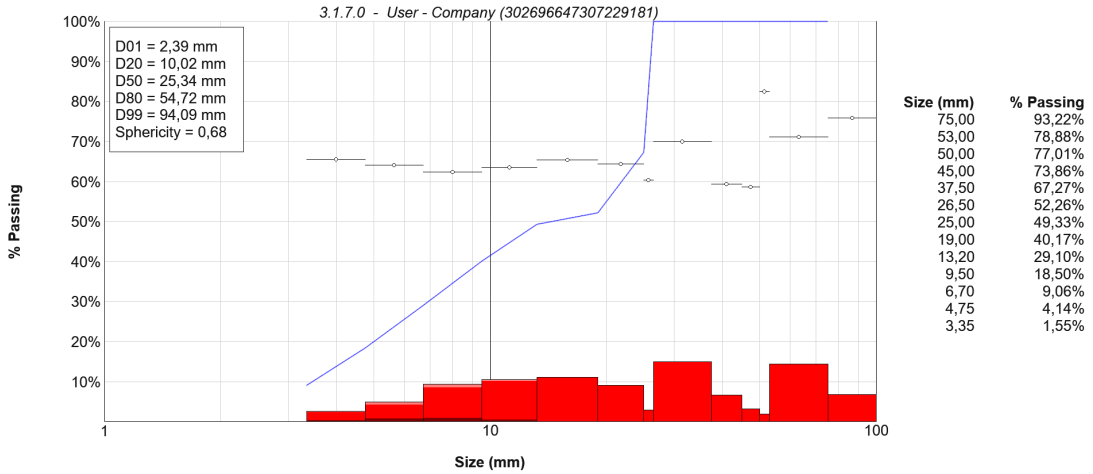
Size (mm)	% Passing
75,00	100,00%
53,00	100,00%
50,00	100,00%
45,00	96,18%
37,50	90,35%
26,50	76,56%
25,00	74,42%
19,00	60,42%
13,20	40,86%
9,50	23,48%
6,70	13,01%
4,75	5,87%
3,35	2,59%

Results set 5 image 2

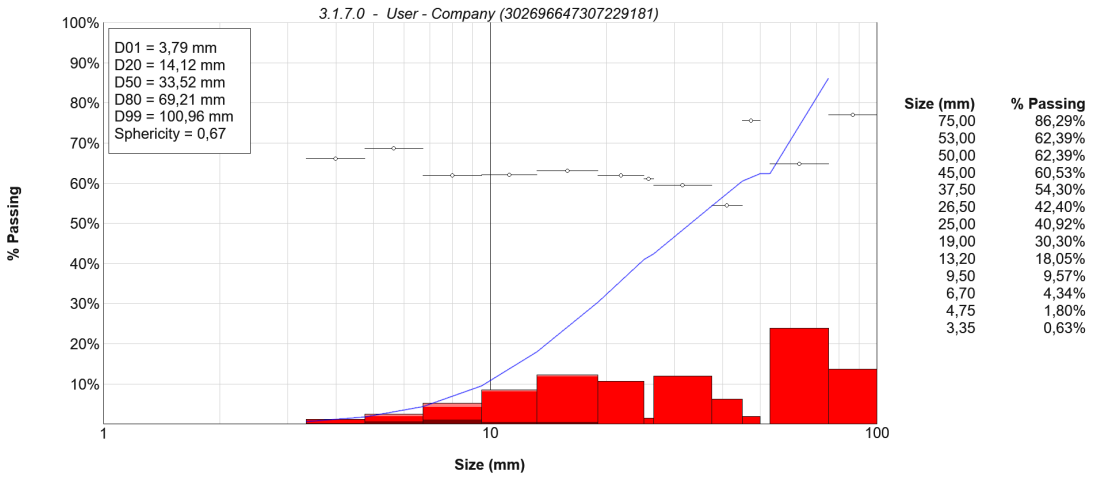


Size (mm)	% Passing
75,00	81,17%
53,00	71,60%
50,00	71,60%
45,00	66,69%
37,50	56,87%
26,50	44,78%
25,00	42,33%
19,00	31,94%
13,20	20,45%
9,50	10,48%
6,70	4,67%
4,75	1,73%
3,35	0,64%

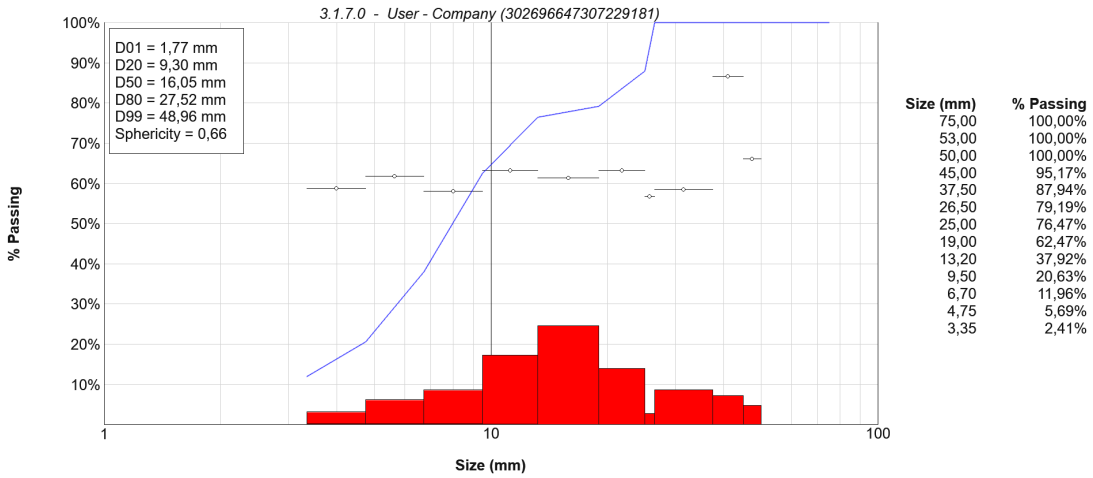
Results set 5 image 3



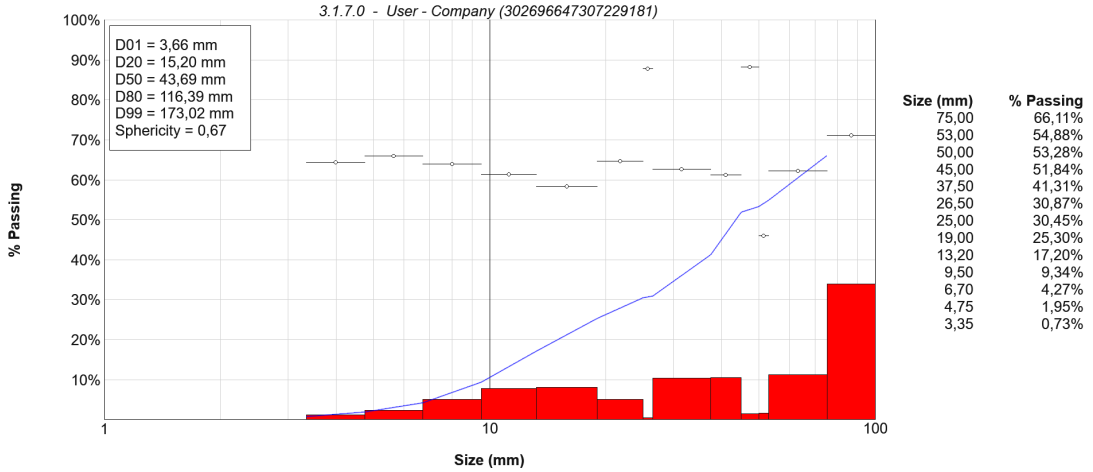
Results set 5 image 4



Results set 5 image 5

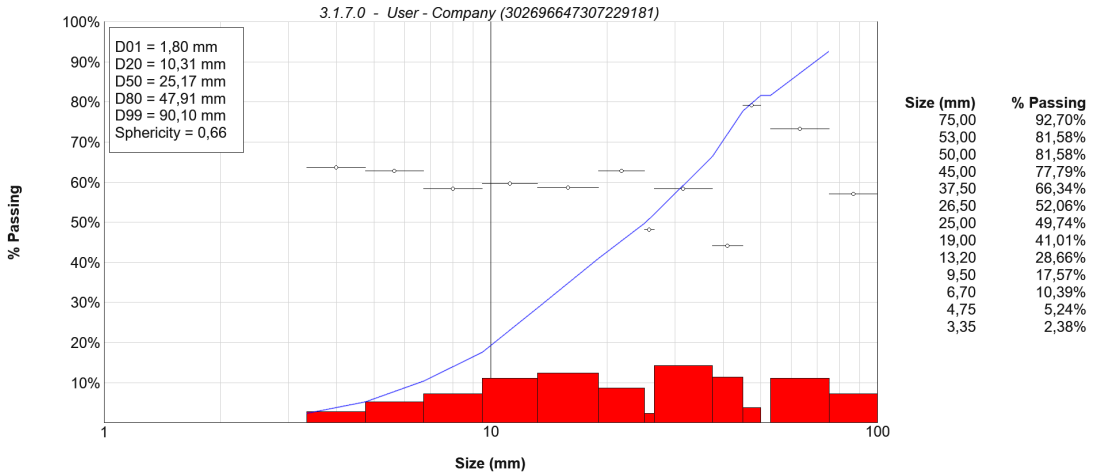


Results set 5 image 6



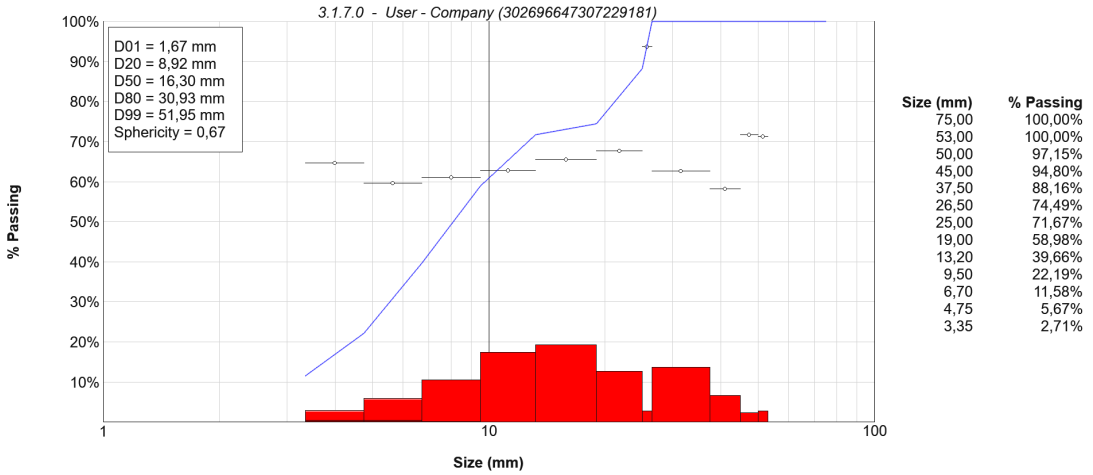
Size (mm)	% Passing
75,00	66,11%
53,00	54,88%
50,00	53,28%
45,00	51,84%
37,50	41,31%
26,50	30,87%
25,00	30,45%
19,00	25,30%
13,20	17,20%
9,50	9,34%
6,70	4,27%
4,75	1,95%
3,35	0,73%

Results set 5 image 7



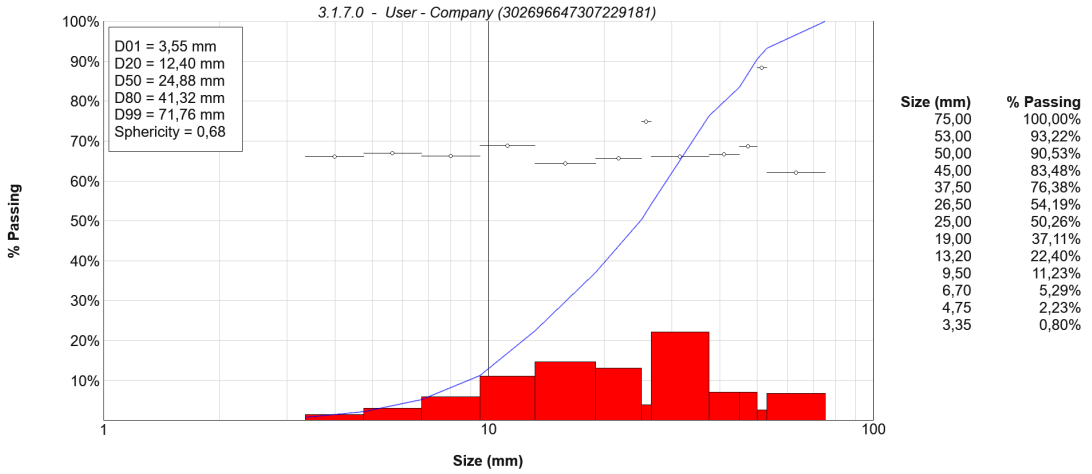
Size (mm)	% Passing
75,00	92,70%
53,00	81,58%
50,00	81,58%
45,00	77,79%
37,50	66,34%
26,50	52,06%
25,00	49,74%
19,00	41,01%
13,20	28,66%
9,50	17,57%
6,70	10,39%
4,75	5,24%
3,35	2,38%

Results set 5 image 8



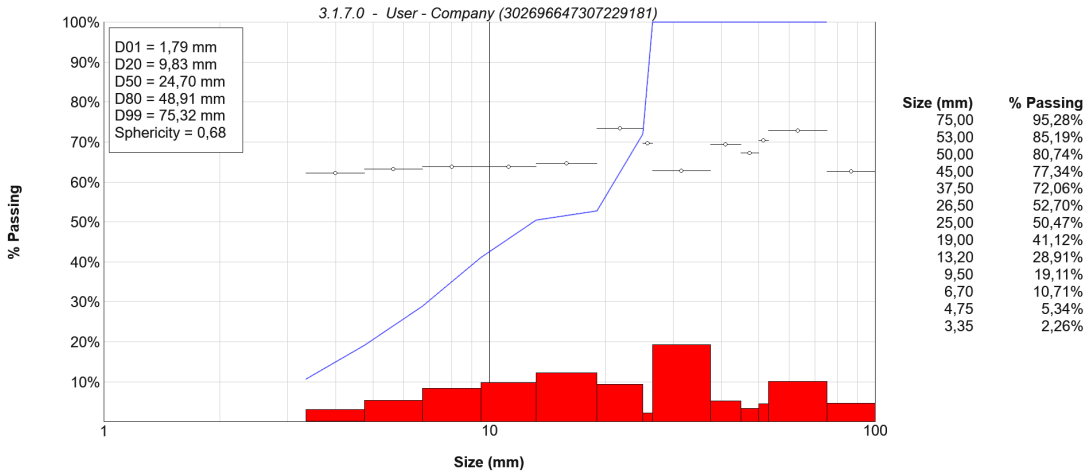
Size (mm)	% Passing
75,00	100,00%
53,00	100,00%
50,00	97,15%
45,00	94,80%
37,50	88,16%
26,50	74,49%
25,00	71,67%
19,00	58,98%
13,20	39,66%
9,50	22,19%
6,70	11,58%
4,75	5,67%
3,35	2,71%

Results set 5 image 9



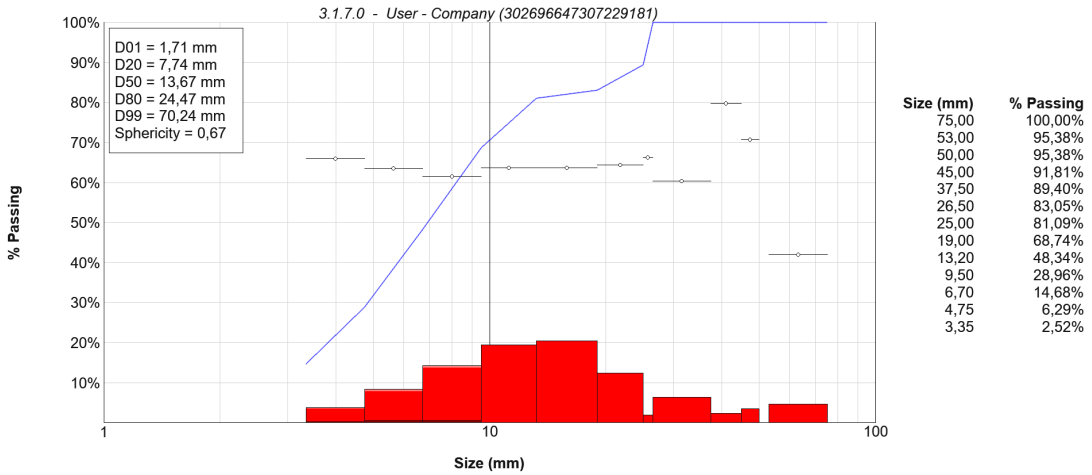
Size (mm)	% Passing
75,00	100,00%
53,00	93,22%
50,00	90,53%
45,00	83,48%
37,50	76,38%
26,50	54,19%
25,00	50,26%
19,00	37,11%
13,20	22,40%
9,50	11,23%
6,70	5,29%
4,75	2,23%
3,35	0,80%

Results set 5 image 10



Size (mm)	% Passing
75,00	95,28%
53,00	85,19%
50,00	80,74%
45,00	77,34%
37,50	72,06%
26,50	52,70%
25,00	50,47%
19,00	41,12%
13,20	28,91%
9,50	19,11%
6,70	10,71%
4,75	5,34%
3,35	2,26%

Results set 5 image 11

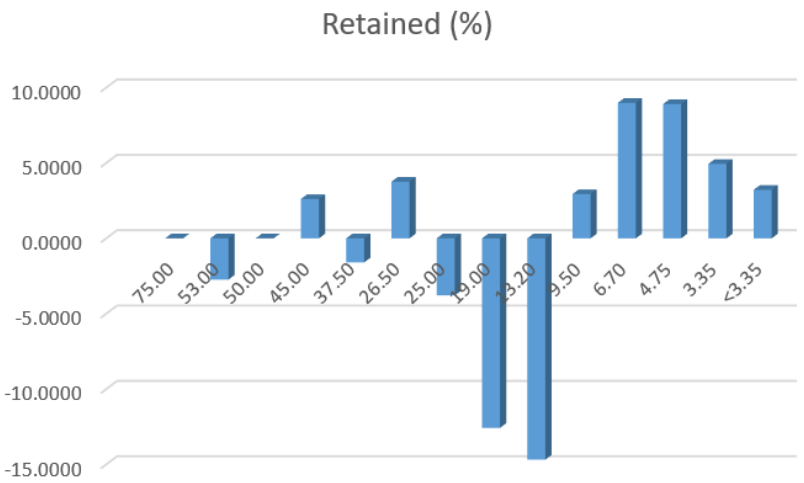


Size (mm)	% Passing
75,00	100,00%
53,00	95,38%
50,00	95,38%
45,00	91,81%
37,50	89,40%
26,50	83,05%
25,00	81,09%
19,00	68,74%
13,20	48,34%
9,50	28,96%
6,70	14,68%
4,75	6,29%
3,35	2,52%

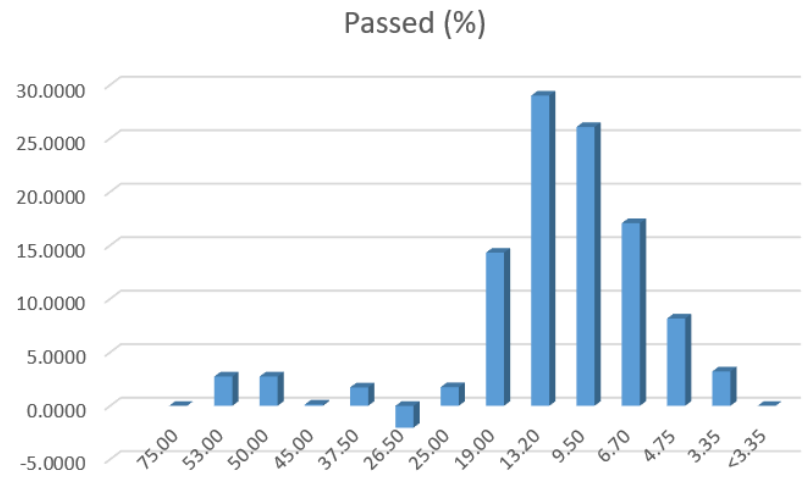
Results set 5 image 12

Difference between sieving and retained/passed percentages for each set

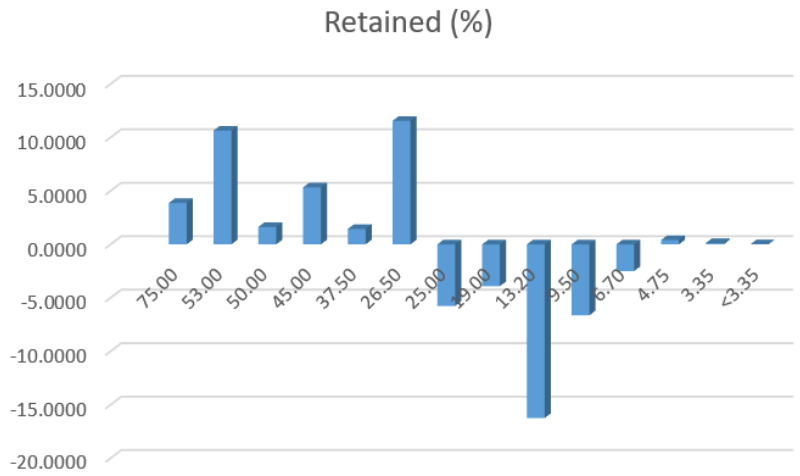
Set number 3



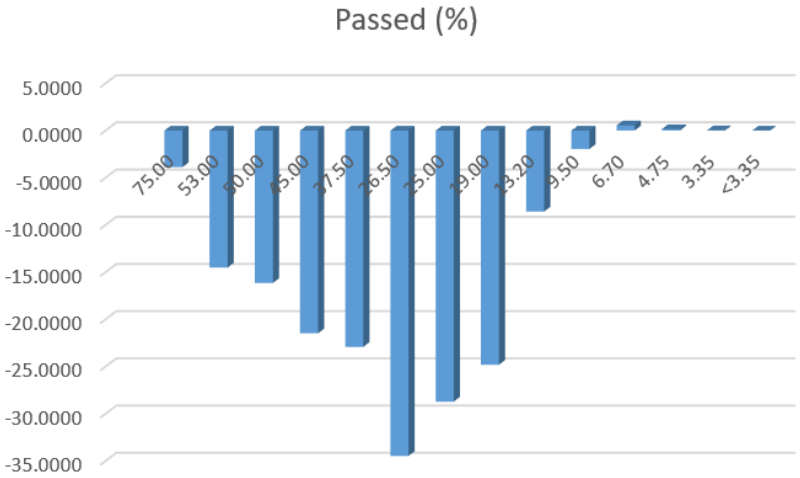
Difference between sieving and set 3 image 1 retained percentage



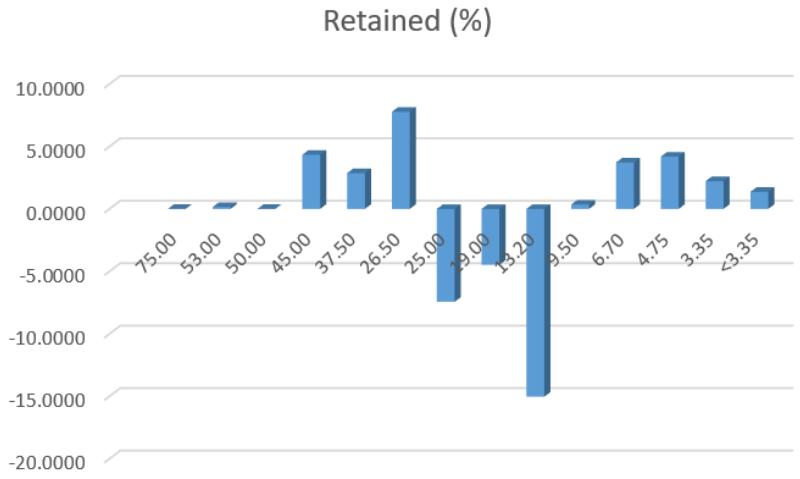
Difference between sieving and set 3 image 1 passed percentage



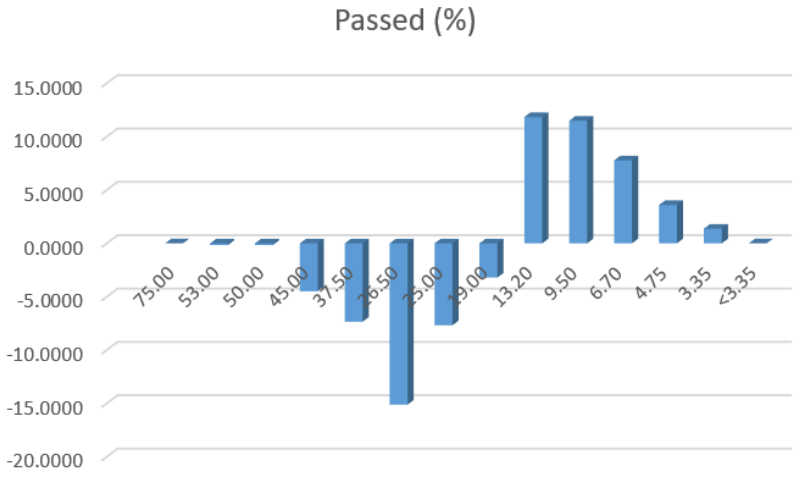
Difference between sieving and set 3 image 2 retained percentage



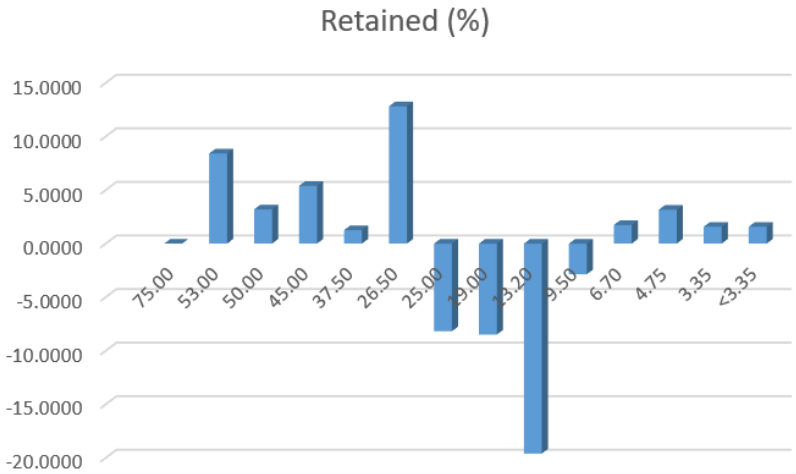
Difference between sieving and set 3 image 2 passed percentage



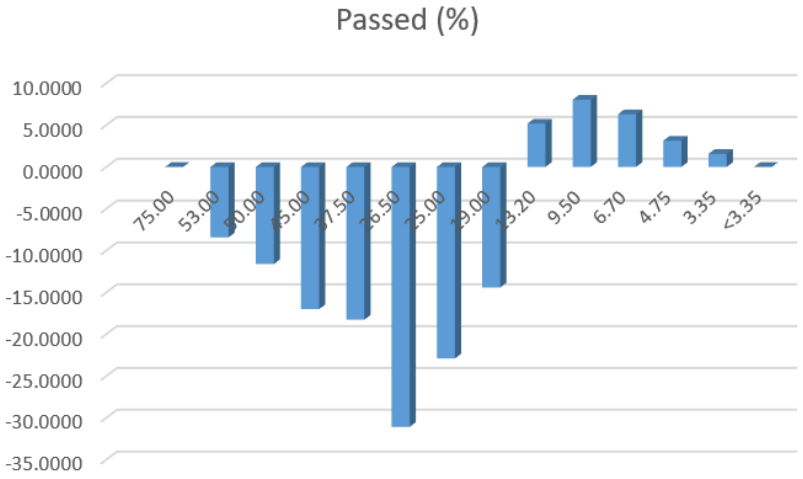
Difference between sieving and set 3 image 3 retained percentage



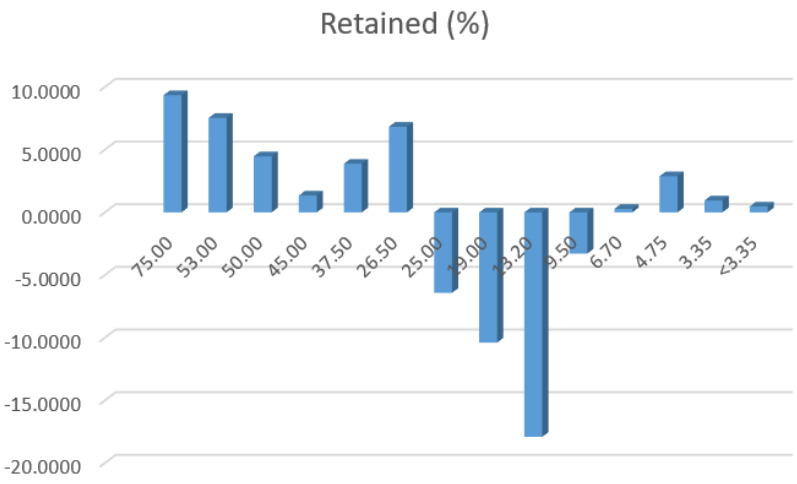
Difference between sieving and set 3 image 3 passed percentage



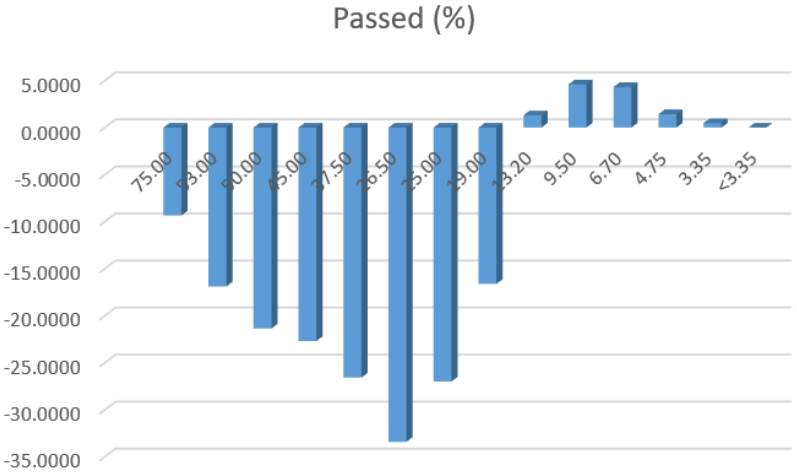
Difference between sieving and set 3 image 4 retained percentage



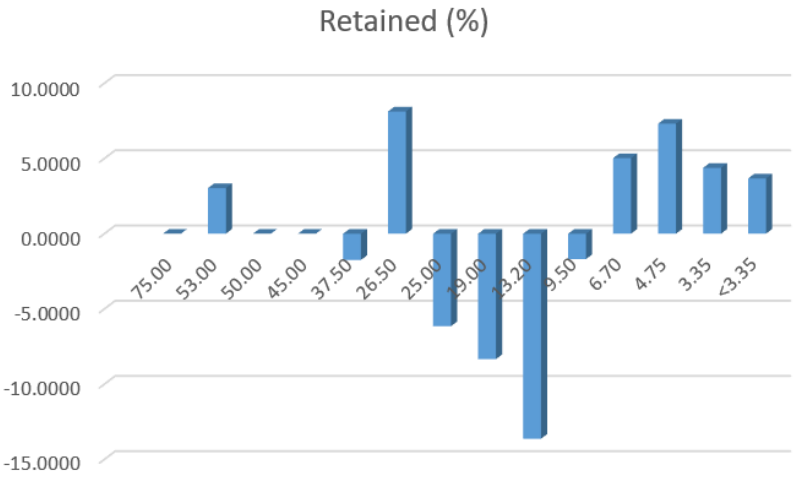
Difference between sieving and set 3 image 4 passed percentage



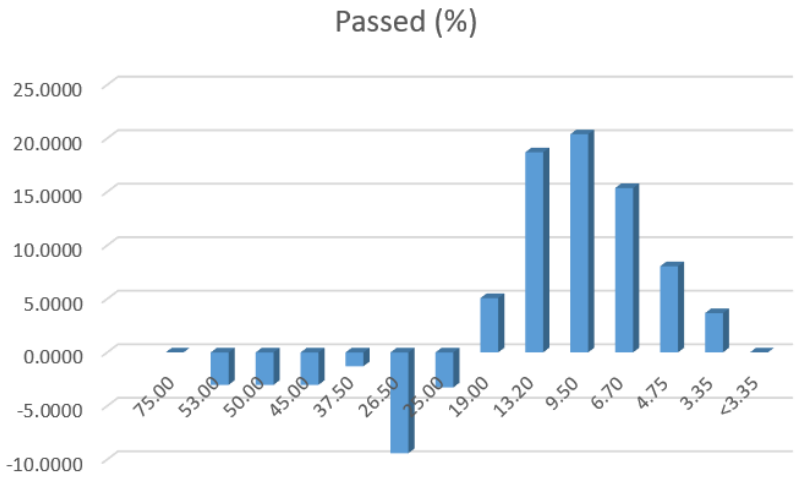
Difference between sieving and set 3 image 5 retained percentage



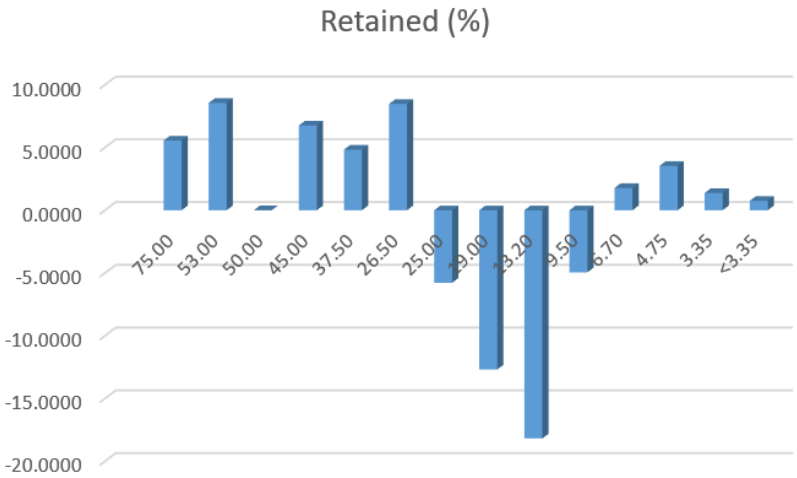
Difference between sieving and set 3 image 5 passed percentage



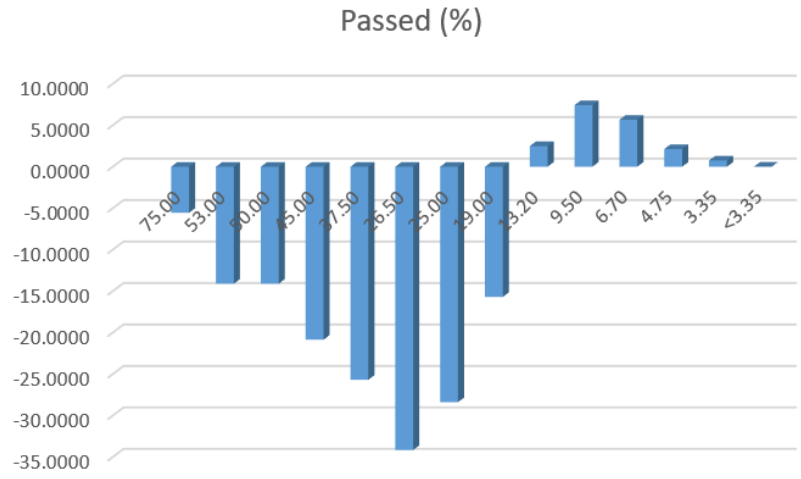
Difference between sieving and set 3 image 6 retained percentage



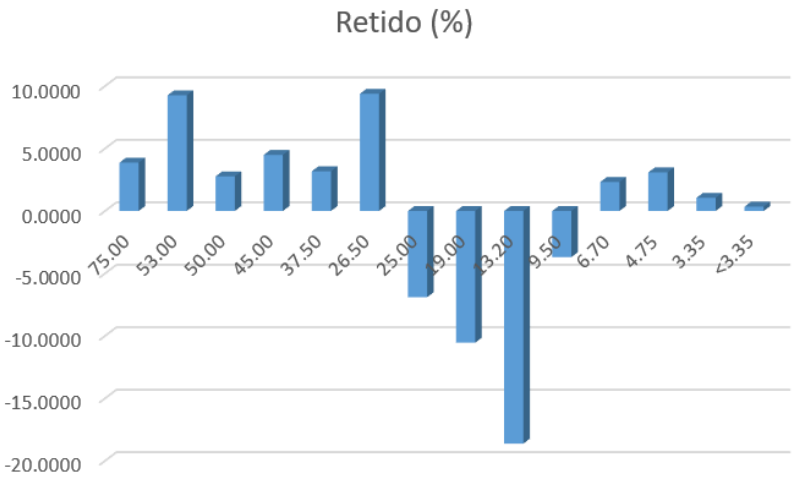
Difference between sieving and set 3 image 6 passed percentage



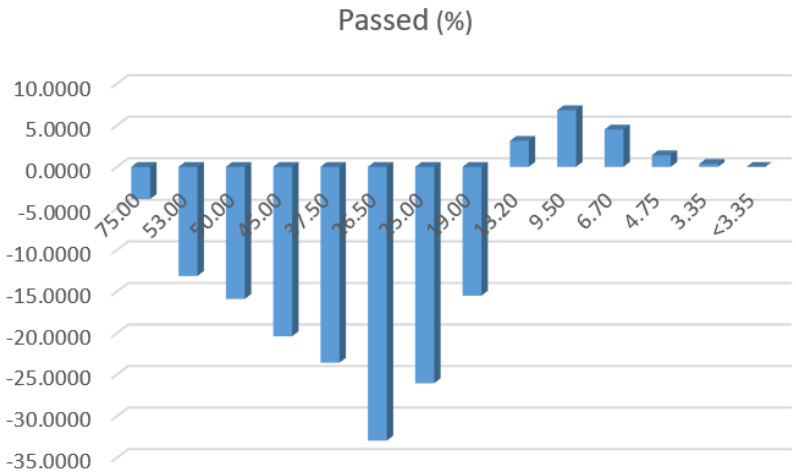
Difference between sieving and set 3 image 7 retained percentage



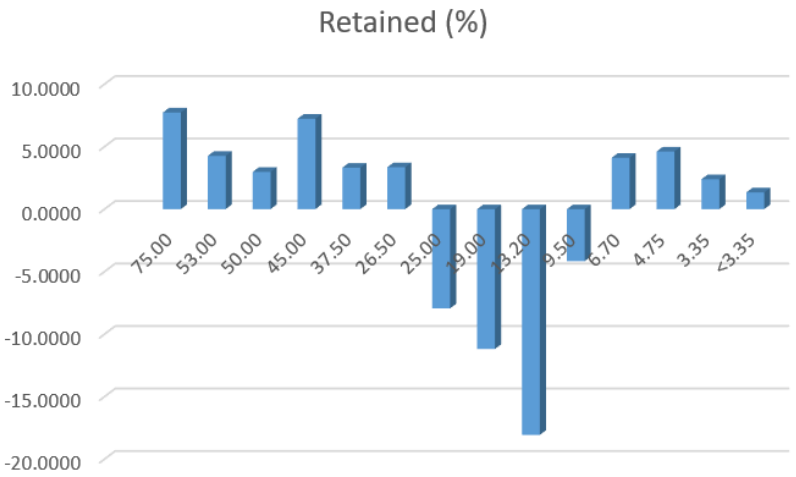
Difference between sieving and set 3 image 7 passed percentage



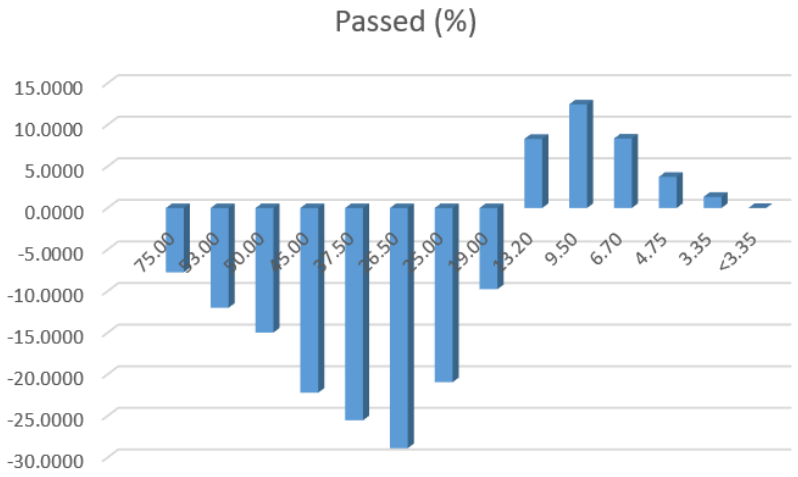
Difference between sieving and set 3 image 7 extra analysis retained percentage



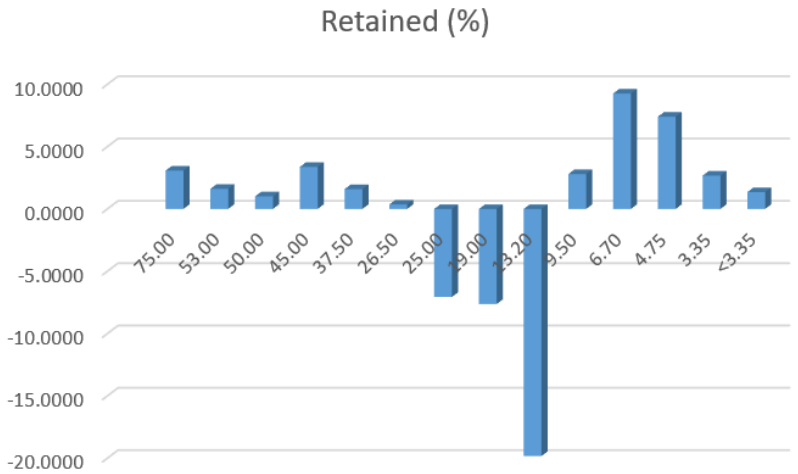
Difference between sieving and set 3 image 7 extra analysis passed percentage



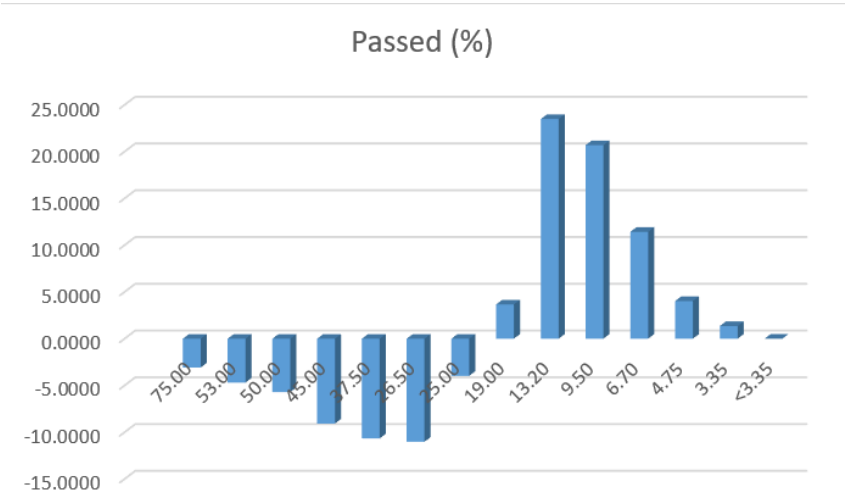
Difference between sieving and set 3 image 8 retained percentage



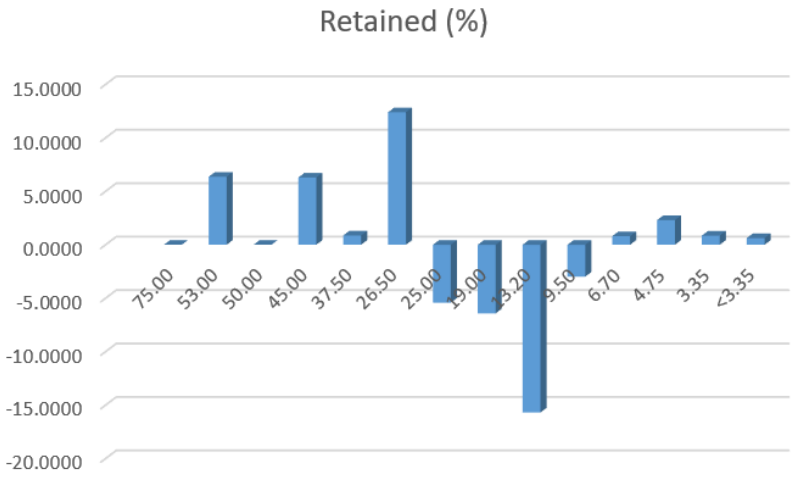
Difference between sieving and set 3 image 8 passed percentage



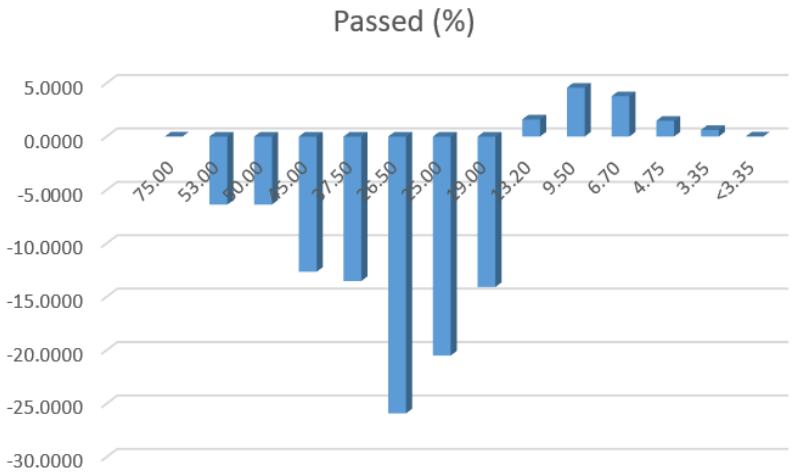
Difference between sieving and set 3 image 8 extra analysis retained percentage



Difference between sieving and set 3 image 8 extra analysis passed percentage

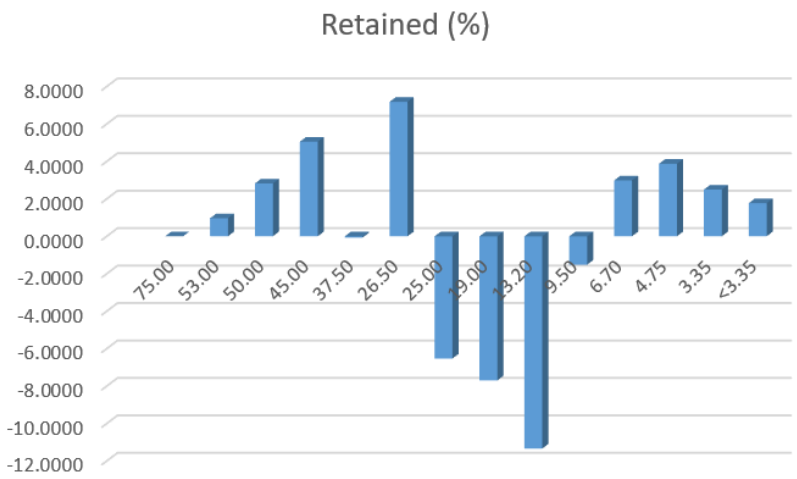


Difference between sieving and set 3 image 9 retained percentage

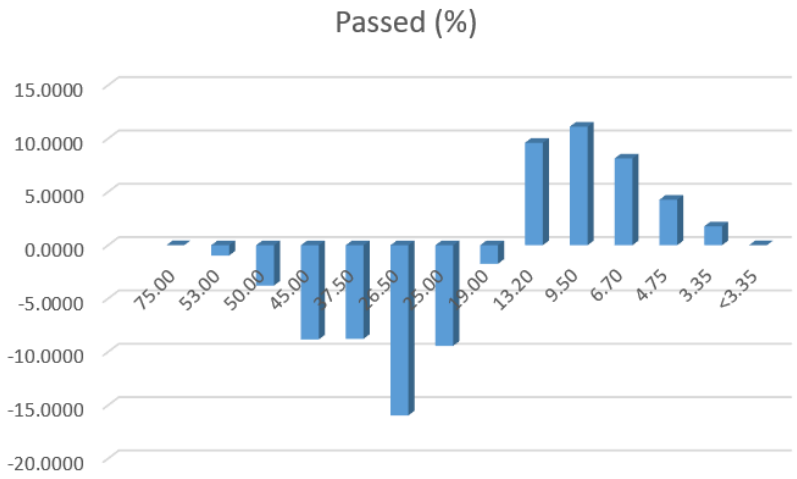


Difference between sieving and set 3 image 9 passed percentage

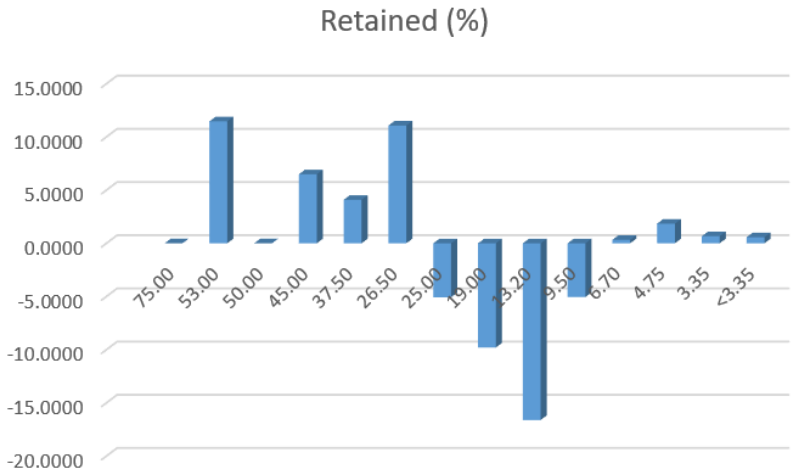
Set number 4



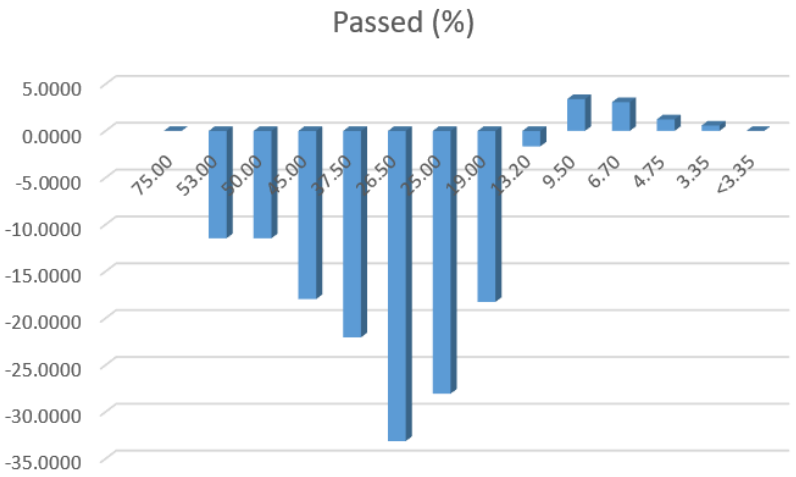
Difference between sieving and set 4 image 1 retained percentage



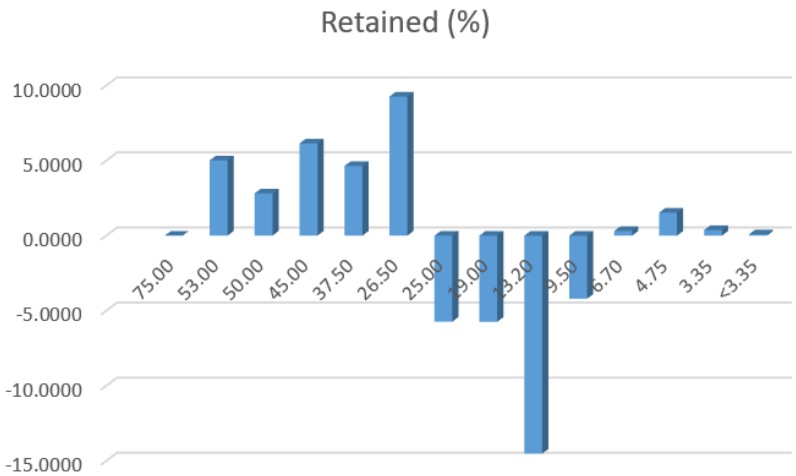
Difference between sieving and set 4 image 1 passed percentage



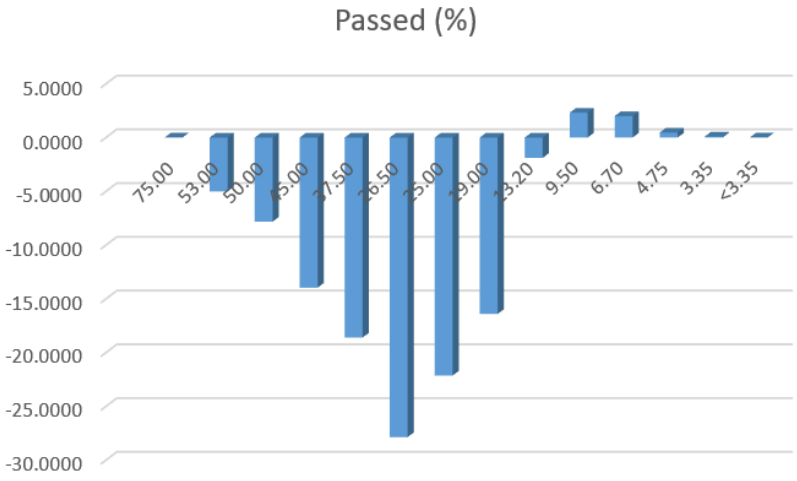
Difference between sieving and set 4 image 2 retained percentage



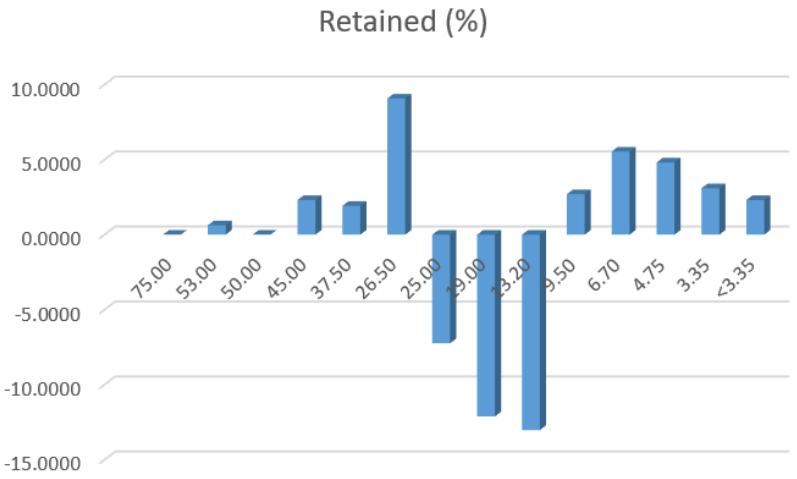
Difference between sieving and set 4 image 2 passed percentage



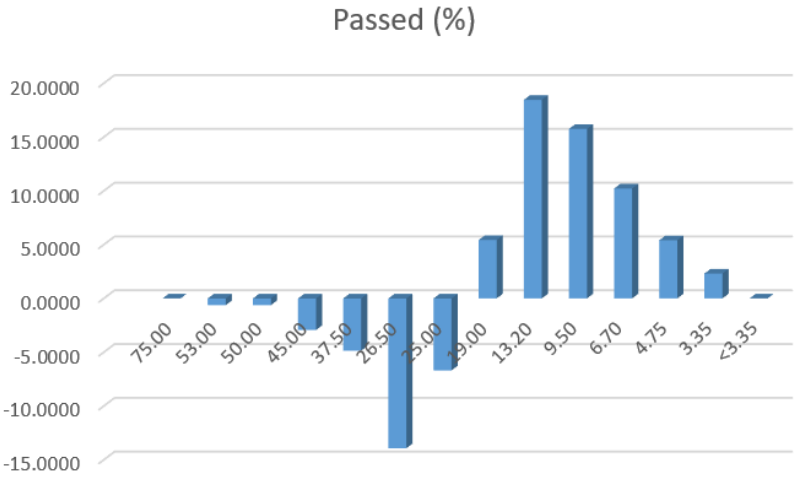
Difference between sieving and set 4 image 3 retained percentage



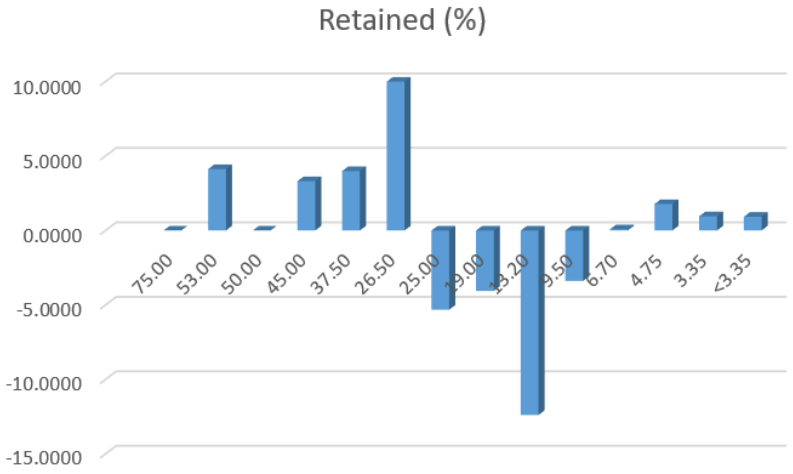
Difference between sieving and set 4 image 3 passed percentage



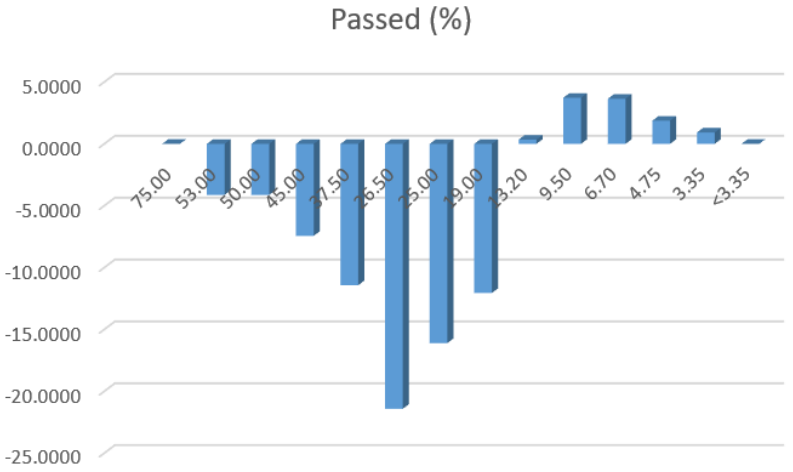
Difference between sieving and set 4 image 4 retained percentage



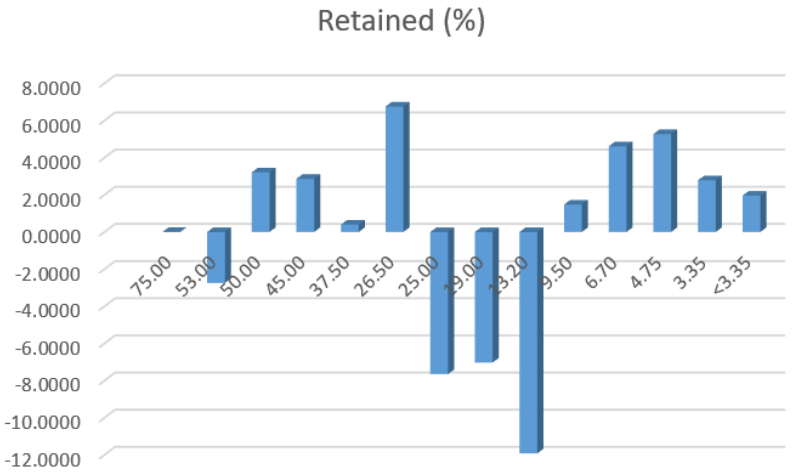
Difference between sieving and set 4 image 4 passed percentage



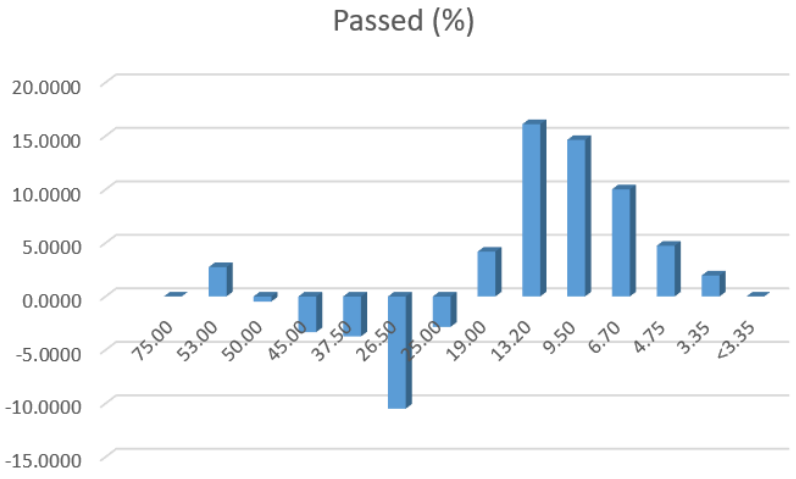
Difference between sieving and set 4 image 5 retained percentage



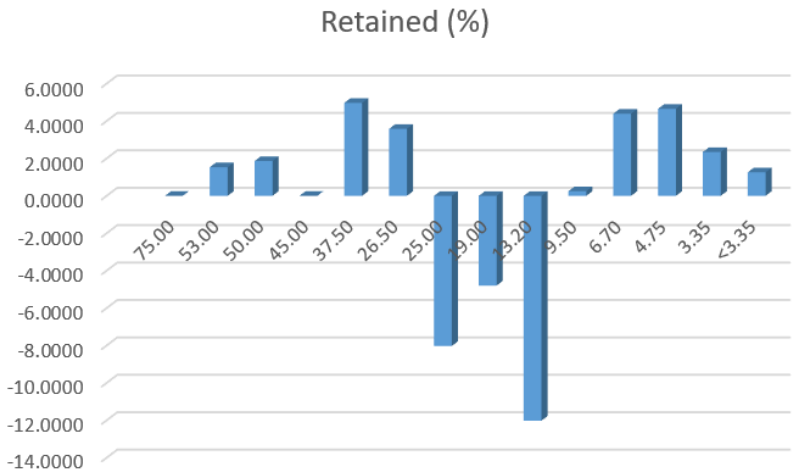
Difference between sieving and set 4 image 5 passed percentage



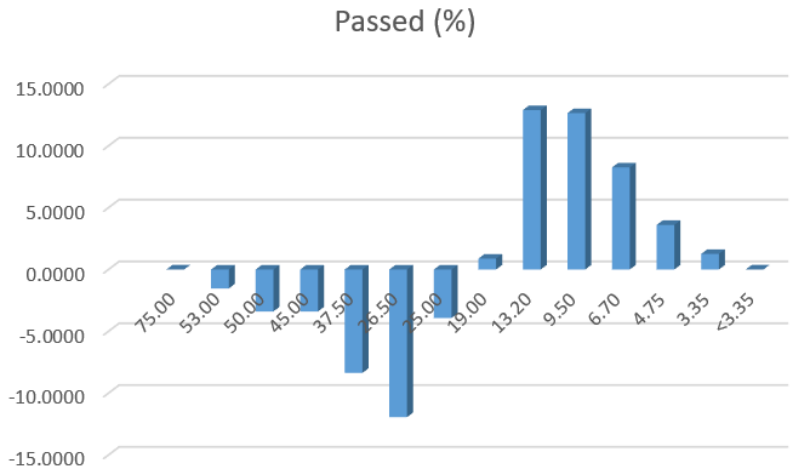
Difference between sieving and set 4 image 6 retained percentage



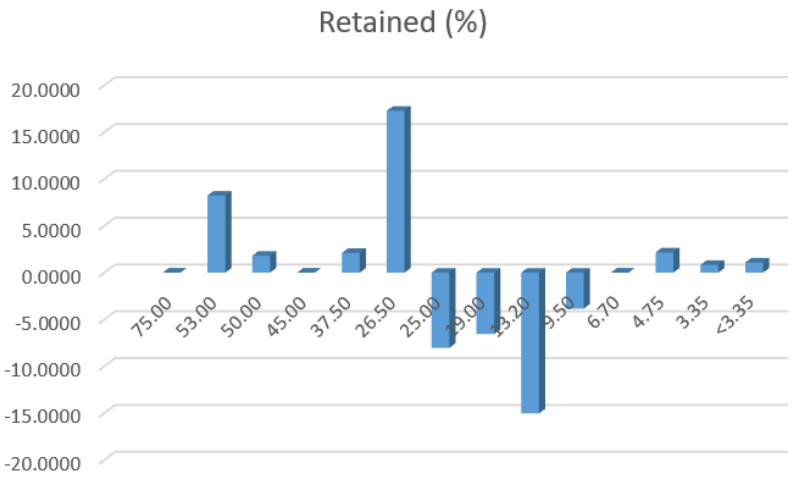
Difference between sieving and set 4 image 6 passed percentage



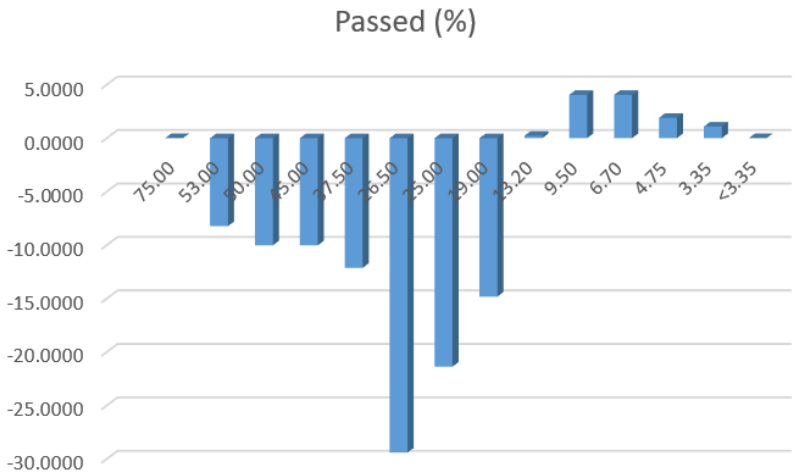
Difference between sieving and set 4 image 7 retained percentage



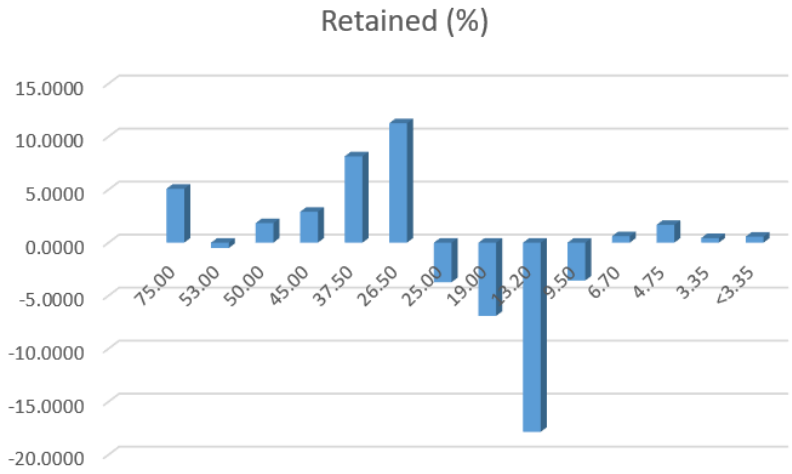
Difference between sieving and set 4 image 7 passed percentage



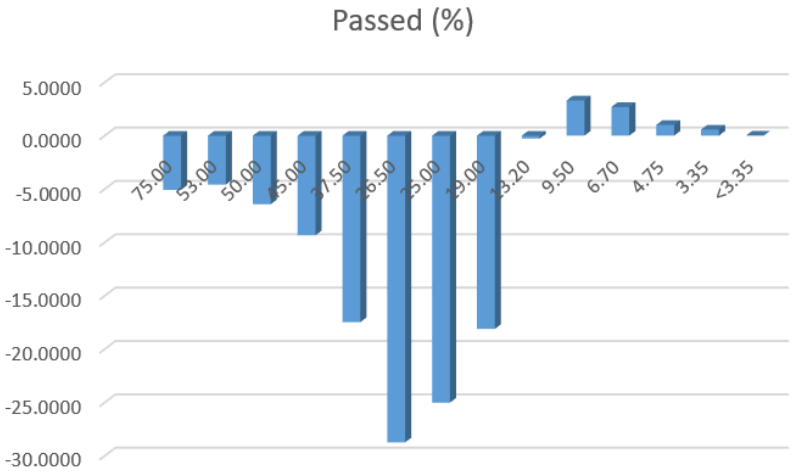
Difference between sieving and set 4 image 8 retained percentage



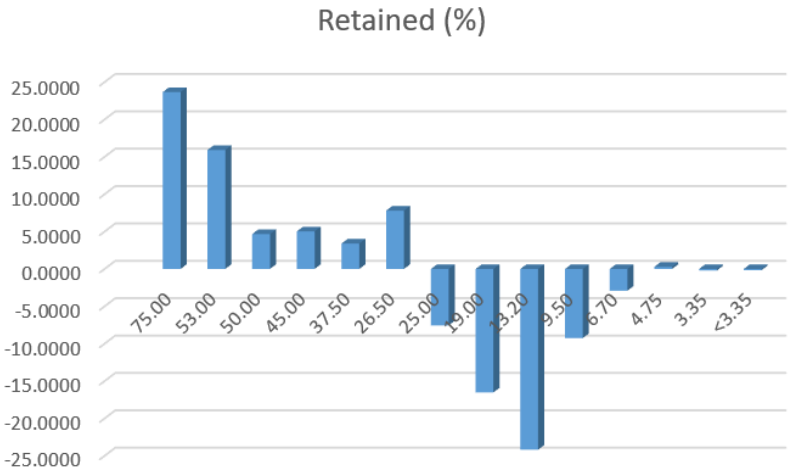
Difference between sieving and set 4 image 8 passed percentage



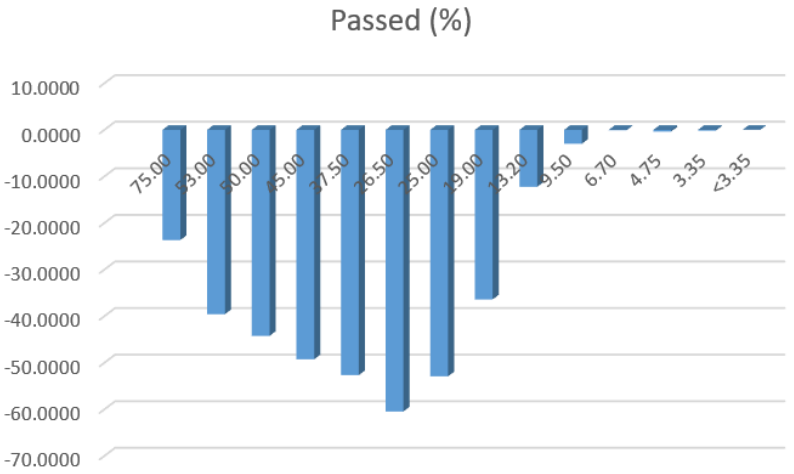
Difference between sieving and set 4 image 9 retained percentage



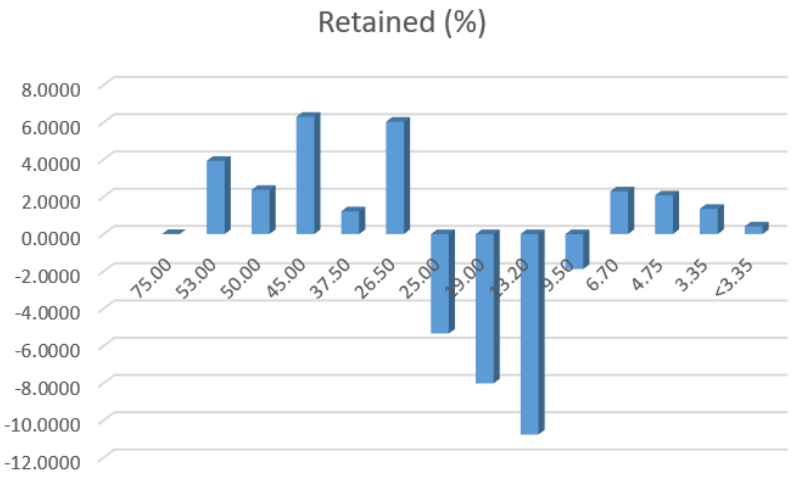
Difference between sieving and set 4 image 9 passed percentage



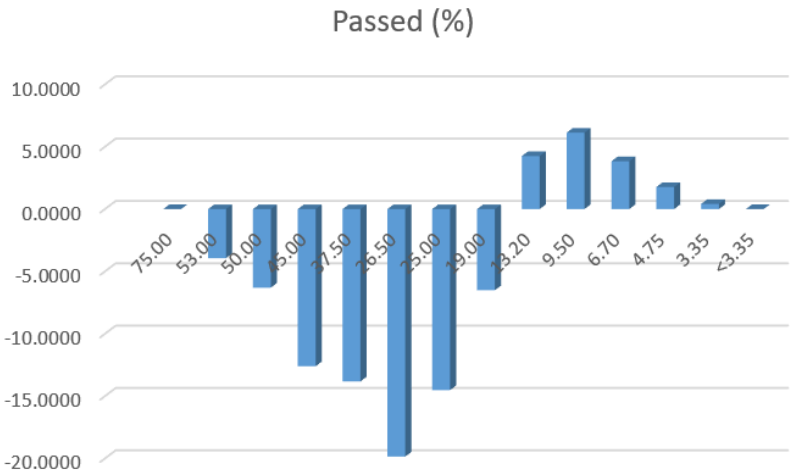
Difference between sieving and set 4 image 10 retained percentage



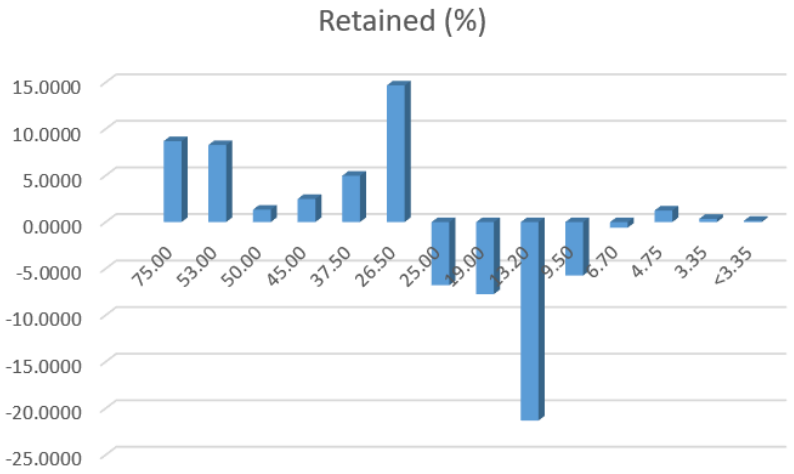
Difference between sieving and set 4 image 10 passed percentage



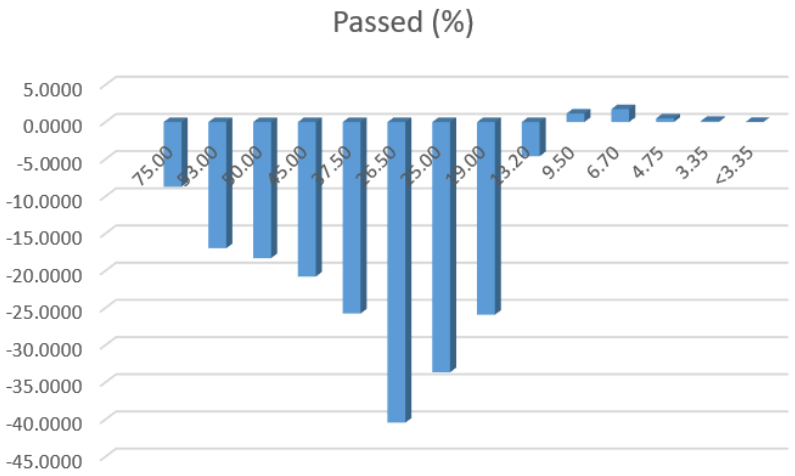
Difference between sieving and set 4 image 11 retained percentage



Difference between sieving and set 4 image 11 passed percentage

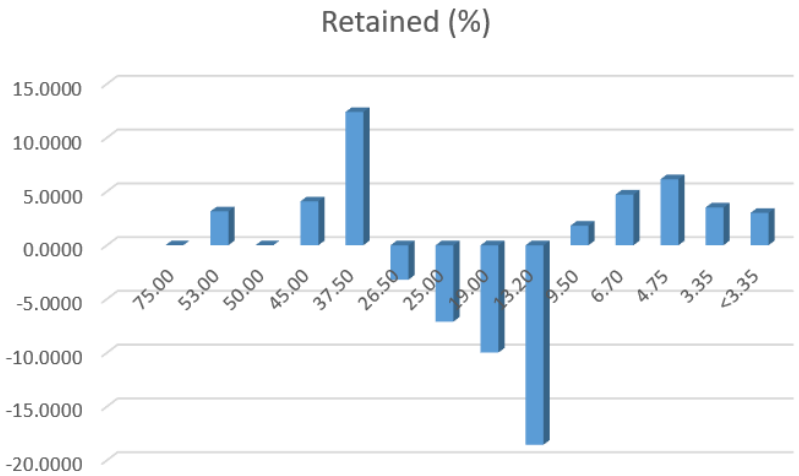


Difference between sieving and set 4 image 12 retained percentage

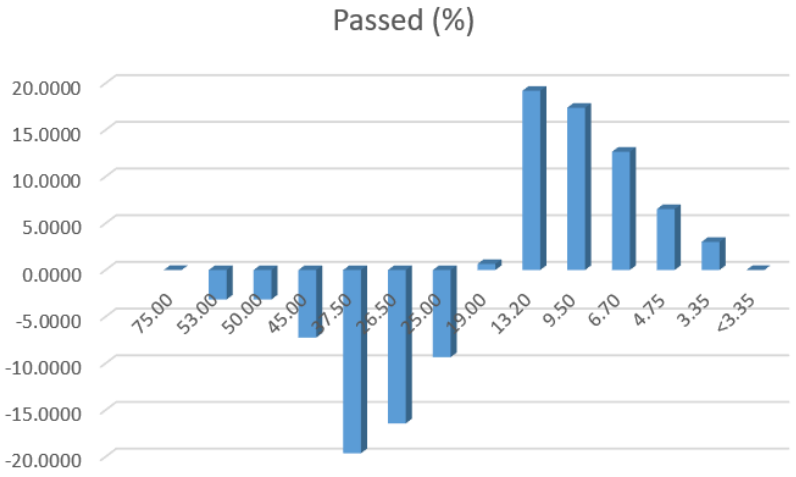


Difference between sieving and set 4 image 12 passed percentage

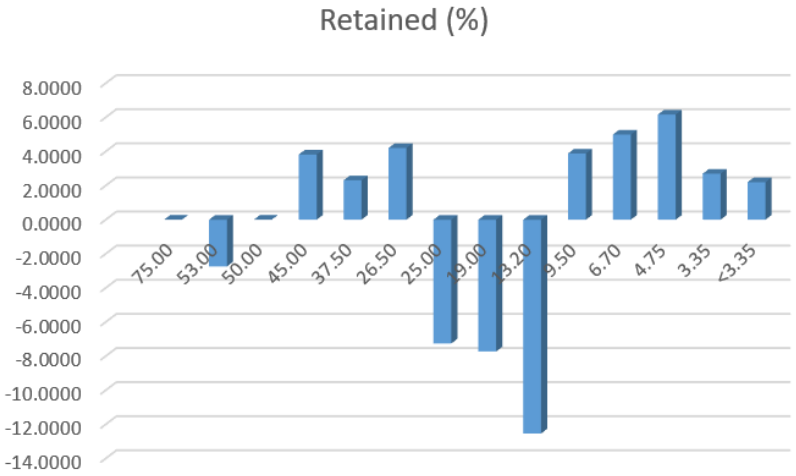
Set number 5



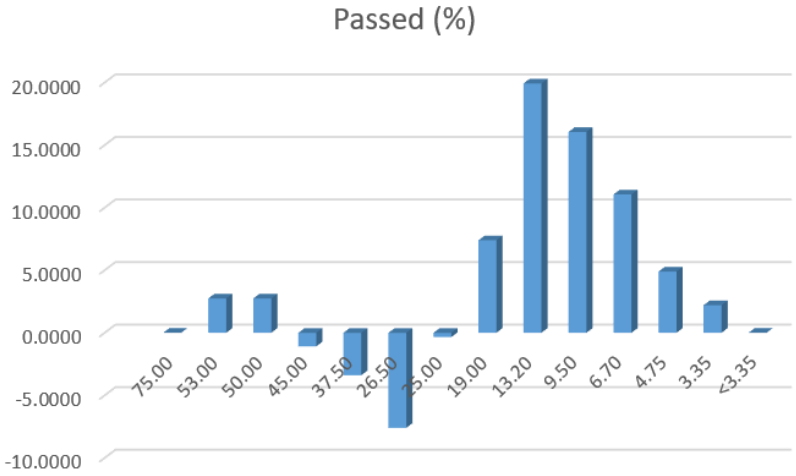
Difference between sieving and set 5 image 1 retained percentage



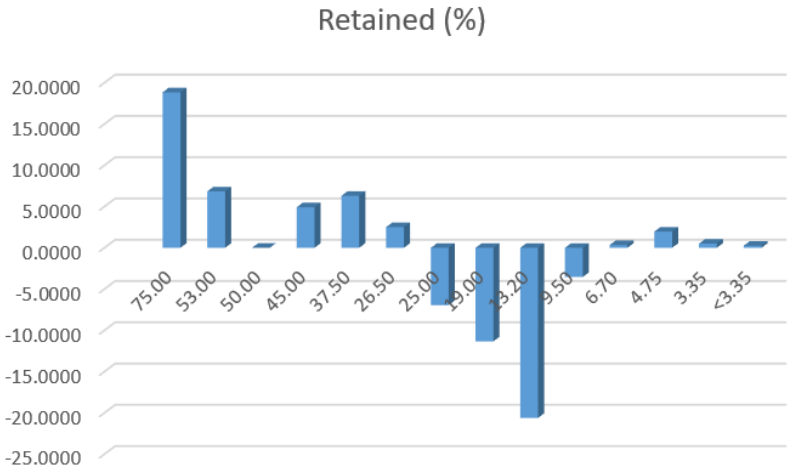
Difference between sieving and set 5 image 1 passed percentage



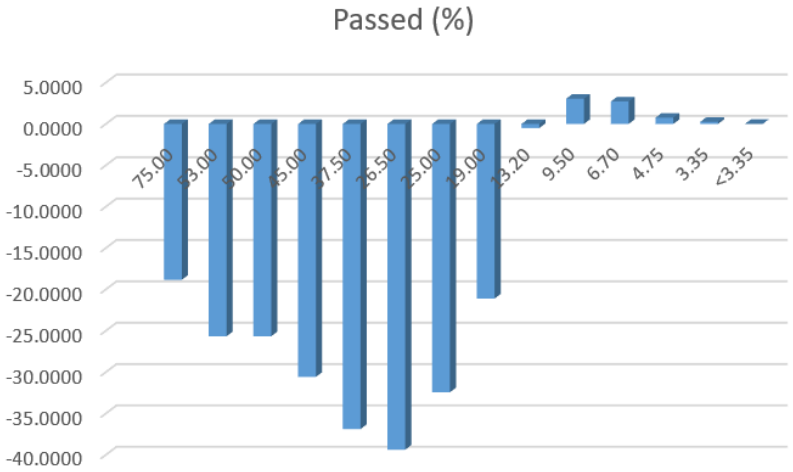
Difference between sieving and set 5 image 2 retained percentage



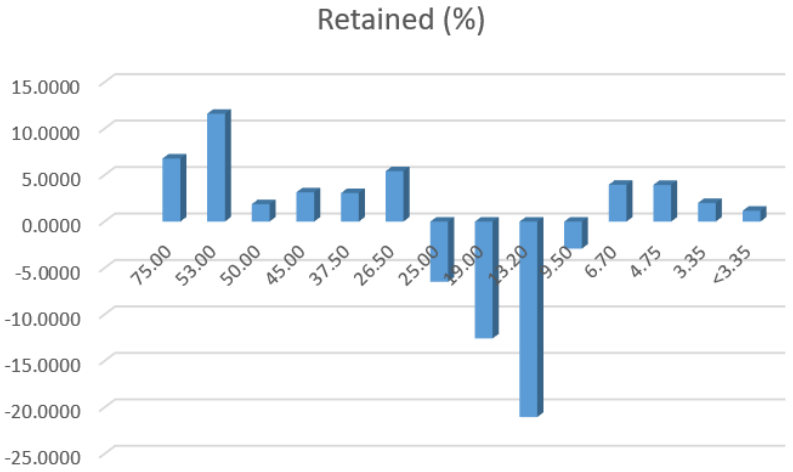
Difference between sieving and set 5 image 2 passed percentage



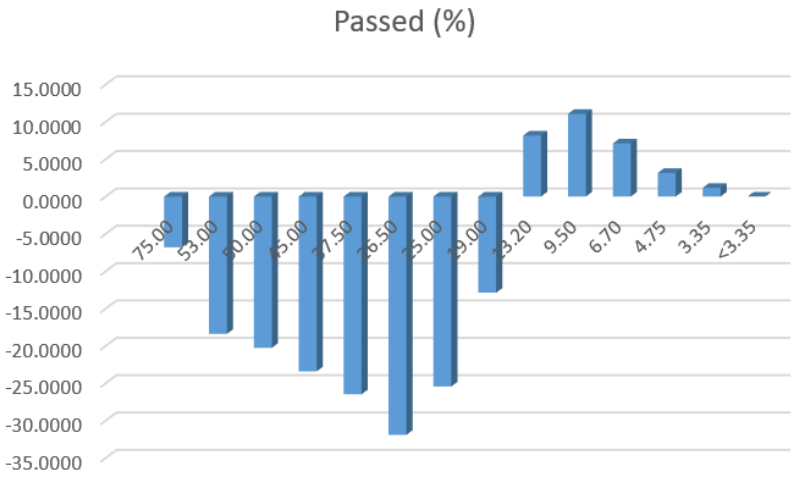
Difference between sieving and set 5 image 3 retained percentage



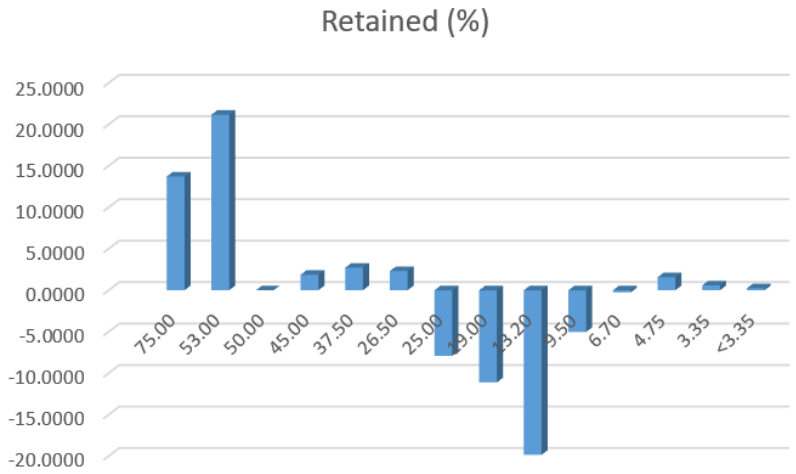
Difference between sieving and set 5 image 3 passed percentage



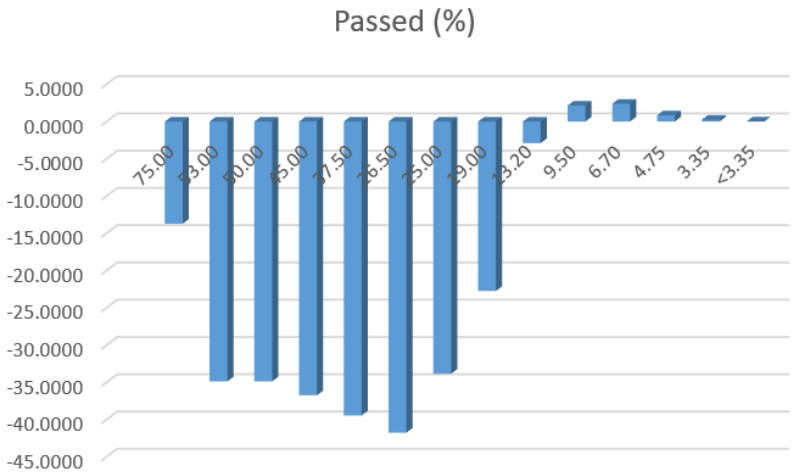
Difference between sieving and set 5 image 4 retained percentage



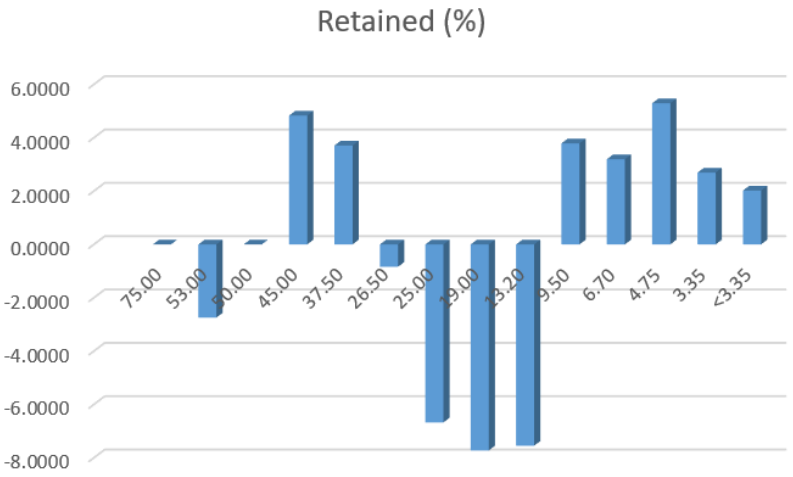
Difference between sieving and set 5 image 4 passed percentage



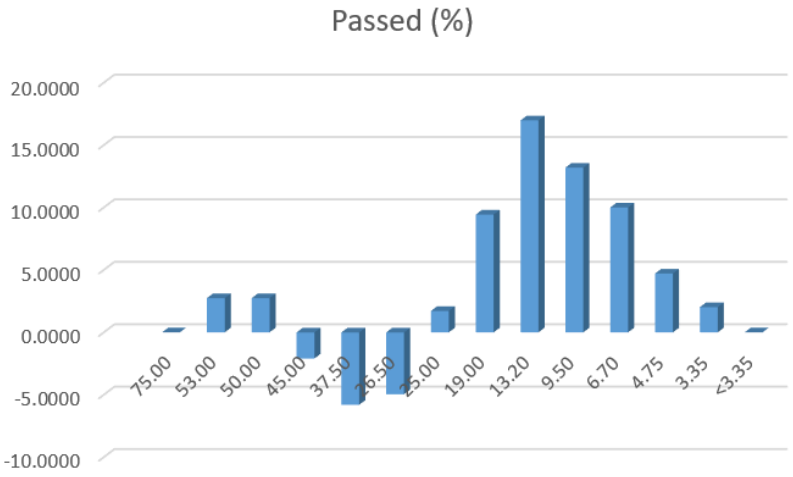
Difference between sieving and set 5 image 5 retained percentage



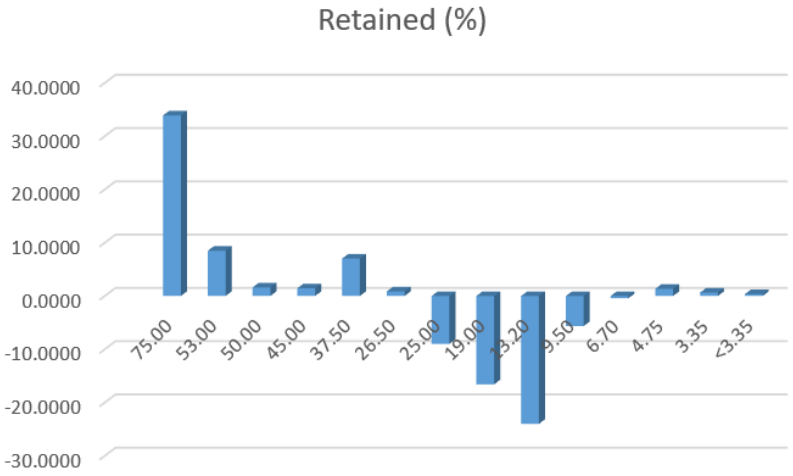
Difference between sieving and set 5 image 5 passed percentage



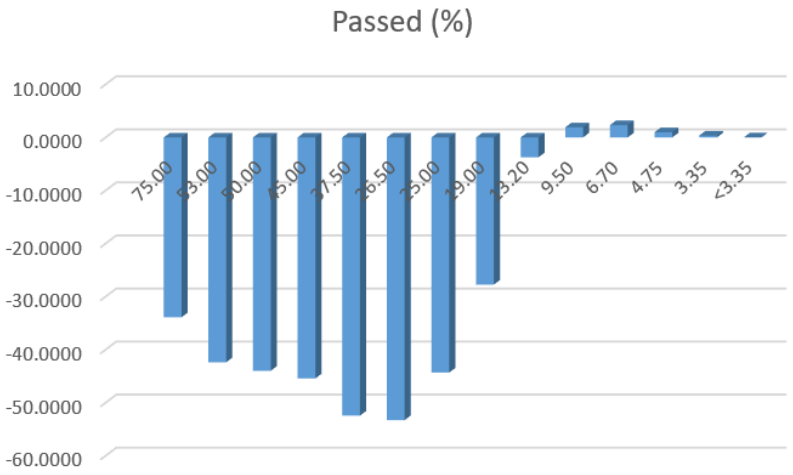
Difference between sieving and set 5 image 6 retained percentage



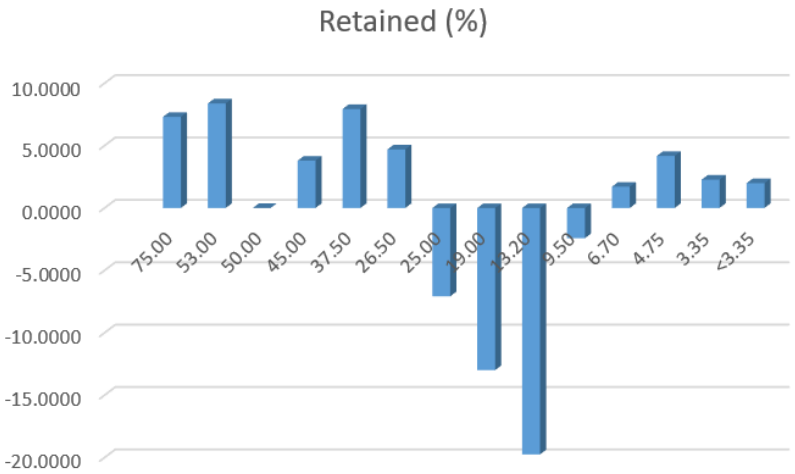
Difference between sieving and set 5 image 6 passed percentage



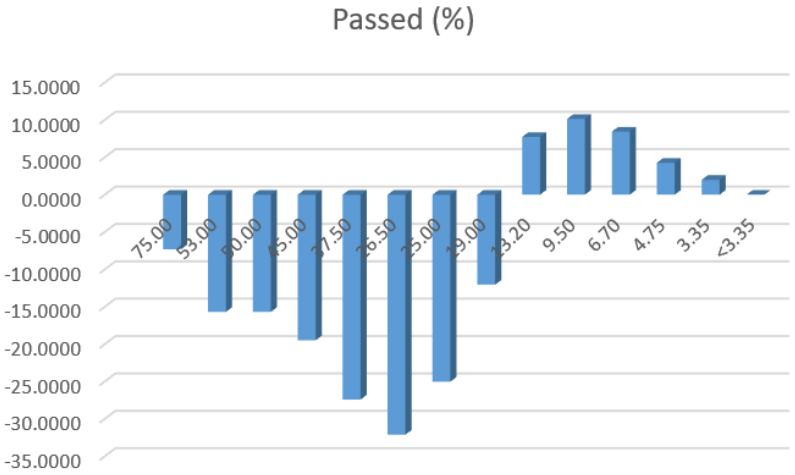
Difference between sieving and set 5 image 7 retained percentage



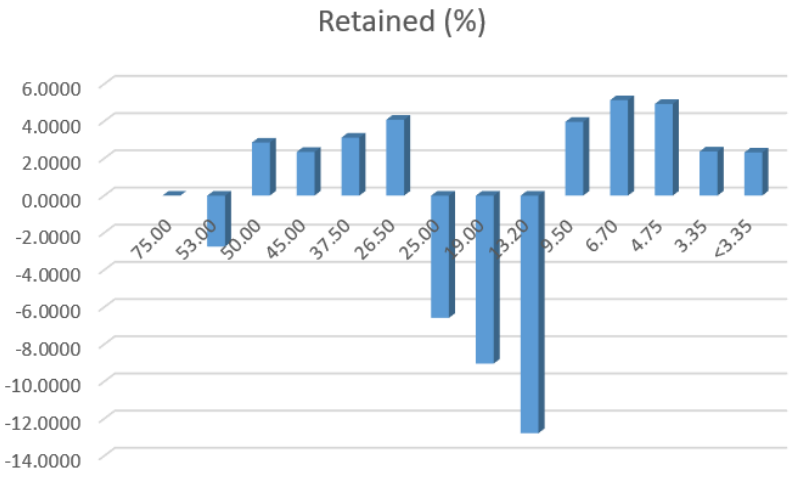
Difference between sieving and set 5 image 7 passed percentage



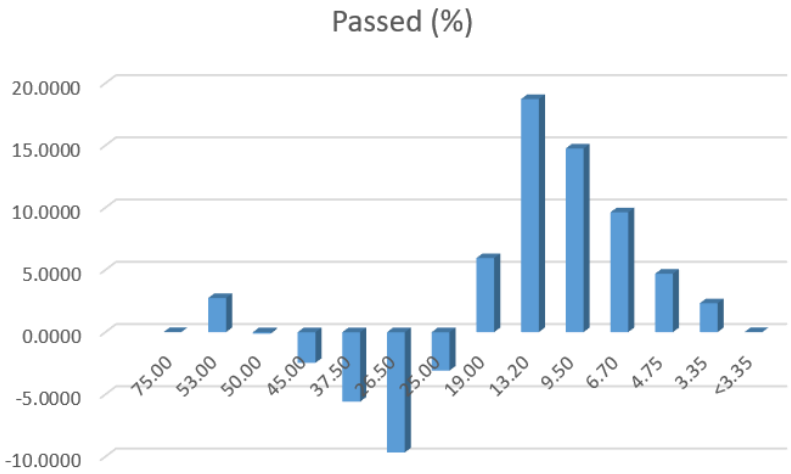
Difference between sieving and set 5 image 8 retained percentage



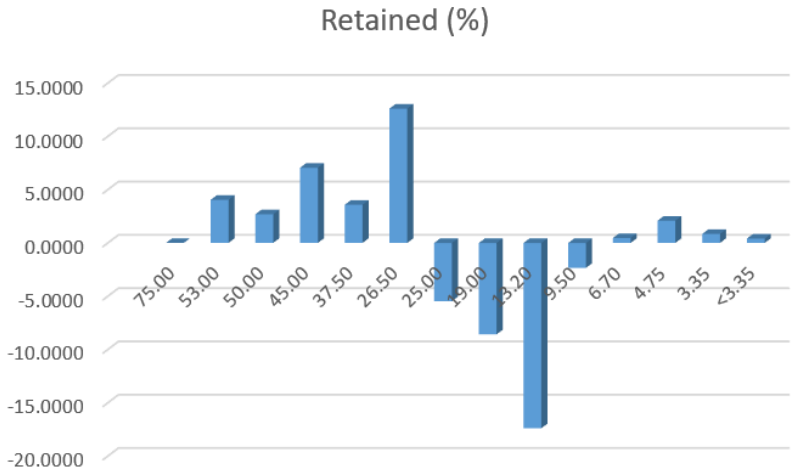
Difference between sieving and set 5 image 8 passed percentage



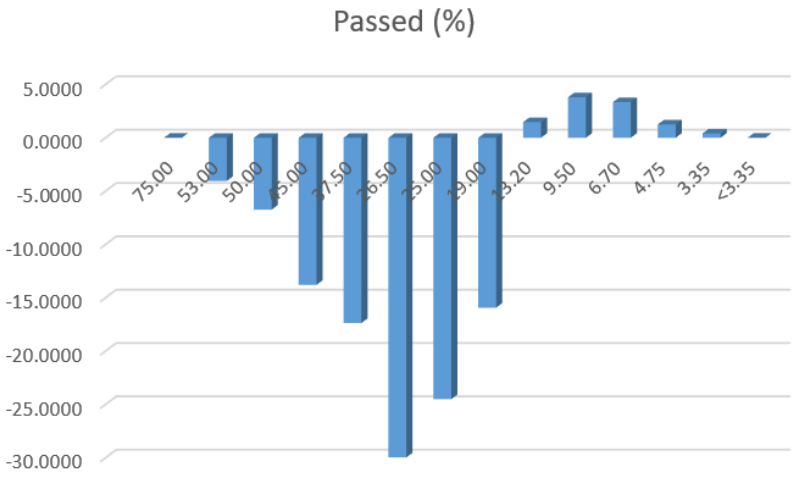
Difference between sieving and set 5 image 9 retained percentage



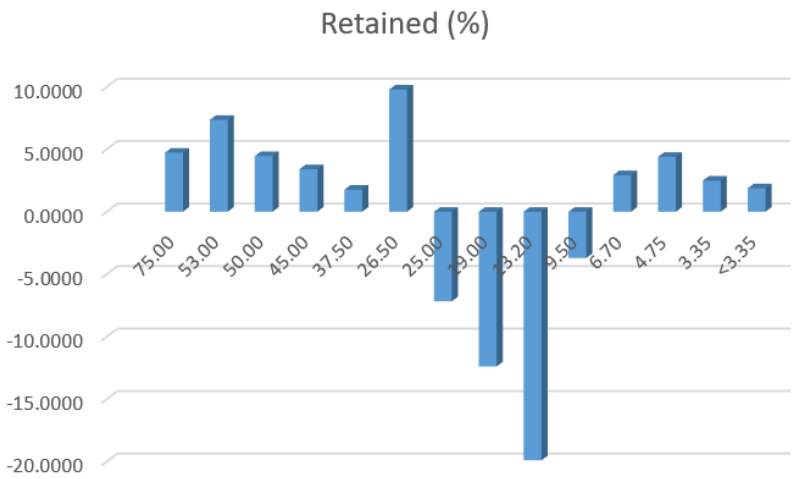
Difference between sieving and set 5 image 9 passed percentage



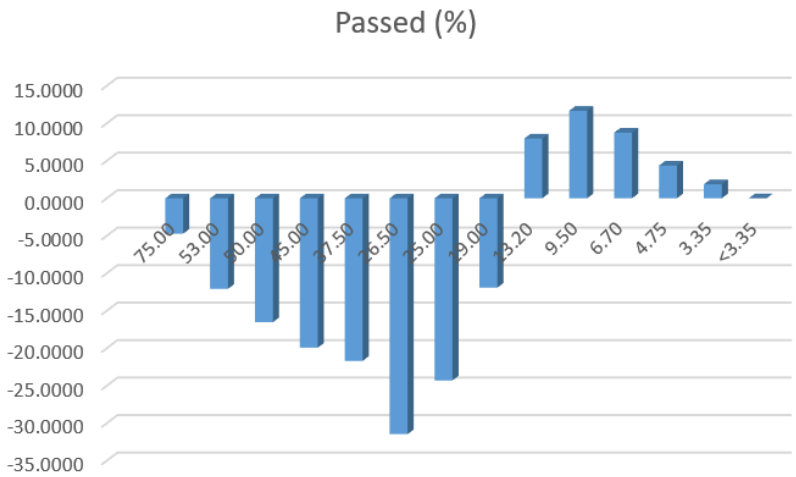
Difference between sieving and set 5 image 10 retained percentage



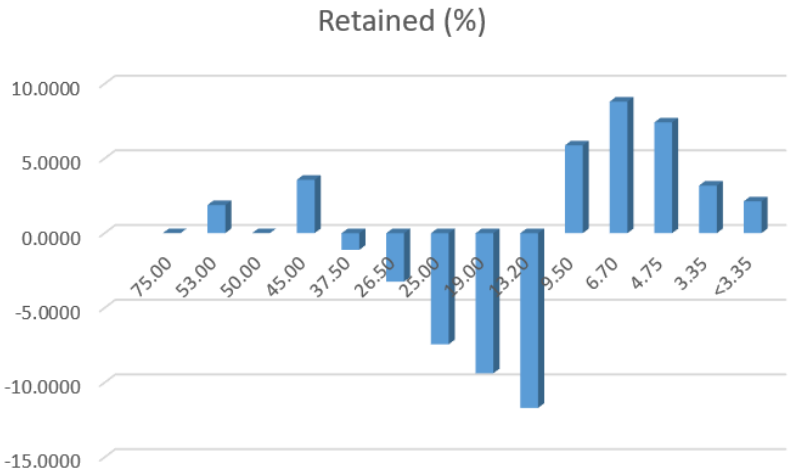
Difference between sieving and set 5 image 10 passed percentage



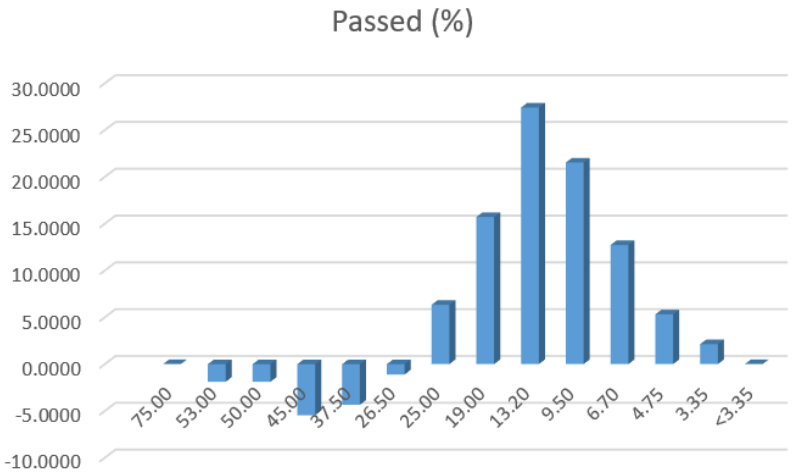
Difference between sieving and set 5 image 11 retained percentage



Difference between sieving and set 5 image 11 passed percentage



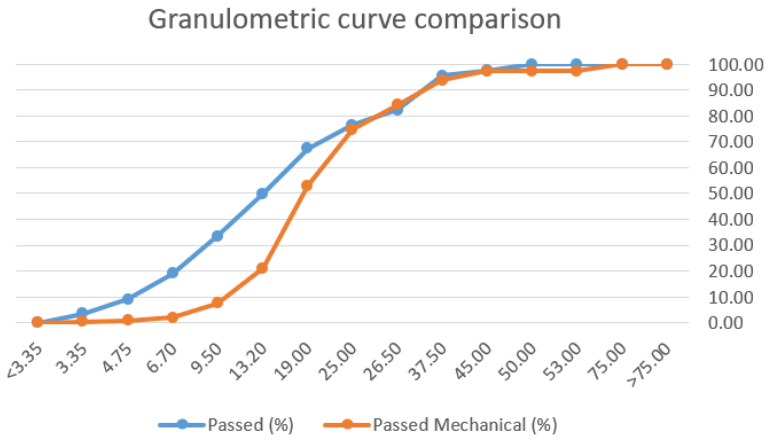
Difference between sieving and set 5 image 12 retained percentage



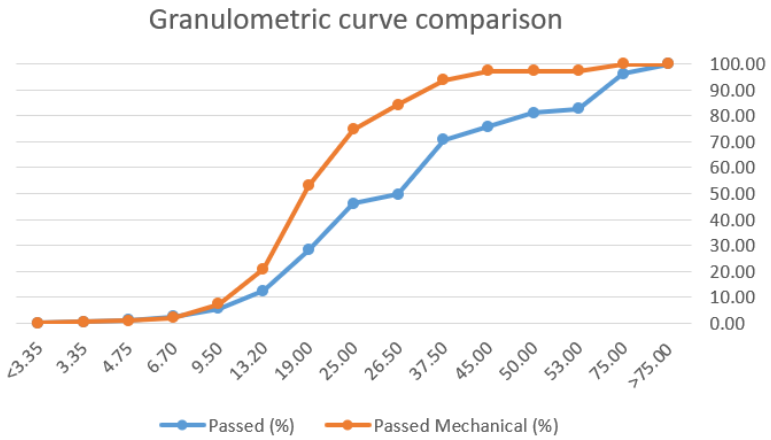
Difference between sieving and set 5 image 12 passed percentage

Comparison between the granulometric curves of the mechanical sieving and each image analysis

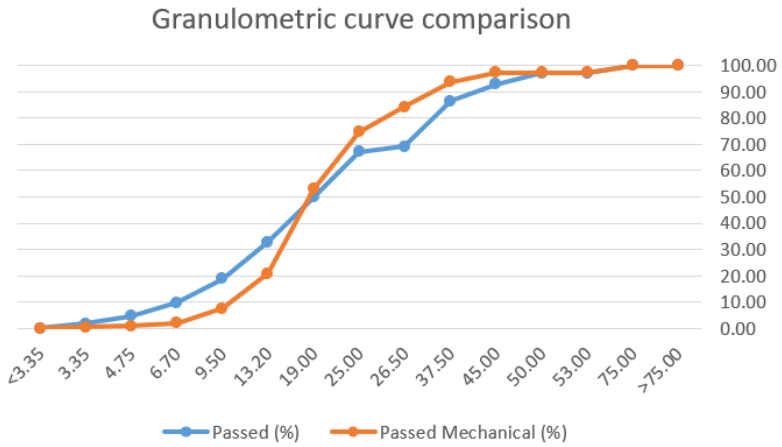
Set number 3



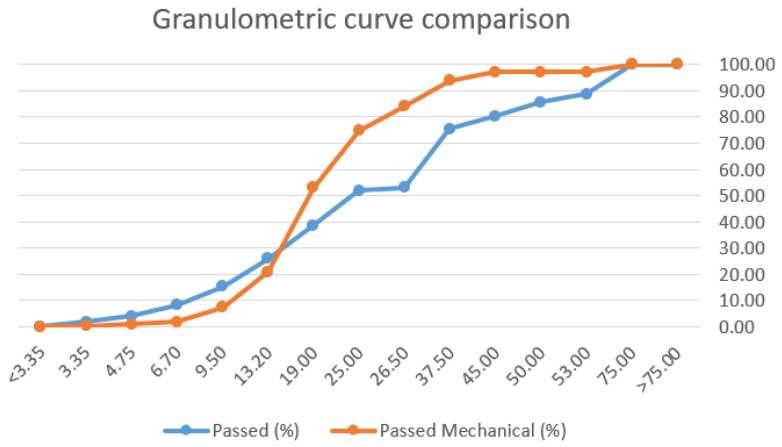
Comparison between the granulometric curves of the mechanical sieving and set 3 image 1 analysis



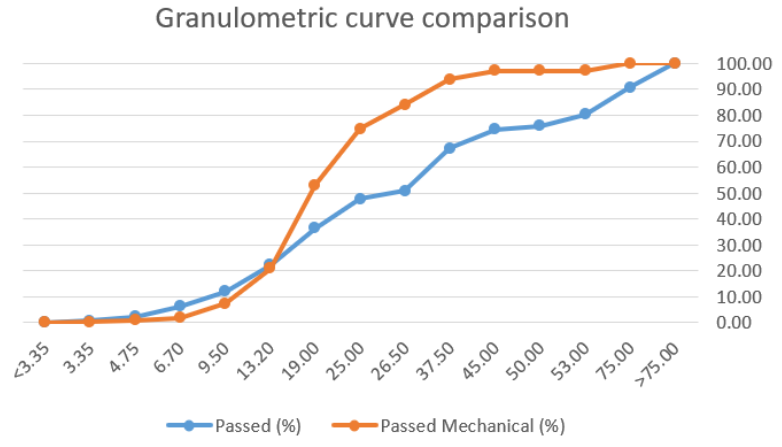
Comparison between the granulometric curves of the mechanical sieving and set 3 image 2 analysis



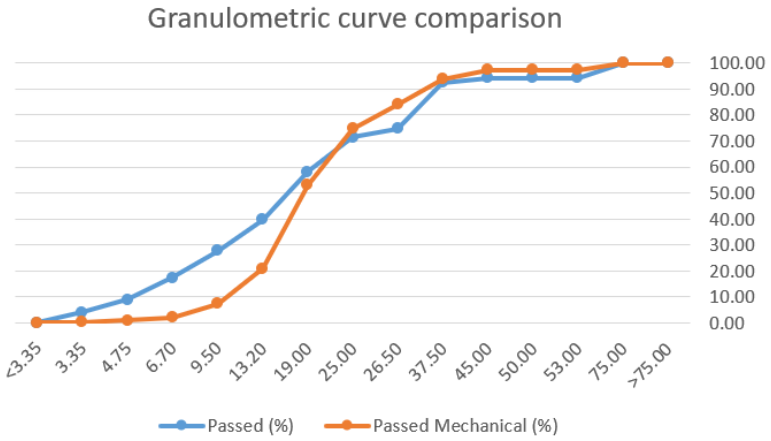
Comparison between the granulometric curves of the mechanical sieving and set 3 image 3 analysis



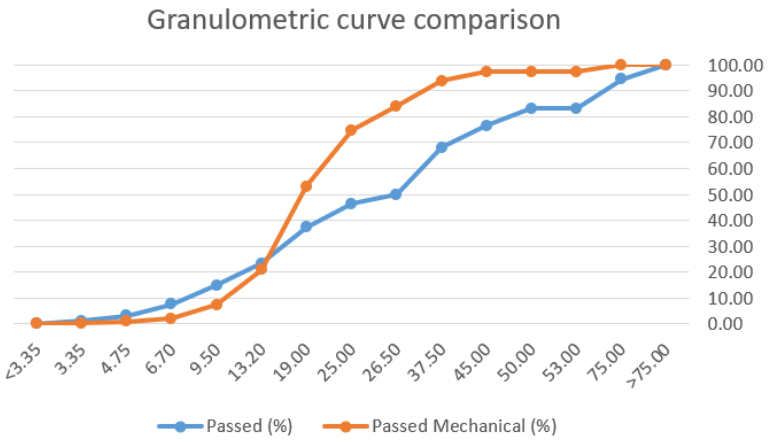
Comparison between the granulometric curves of the mechanical sieving and set 3 image 4 analysis



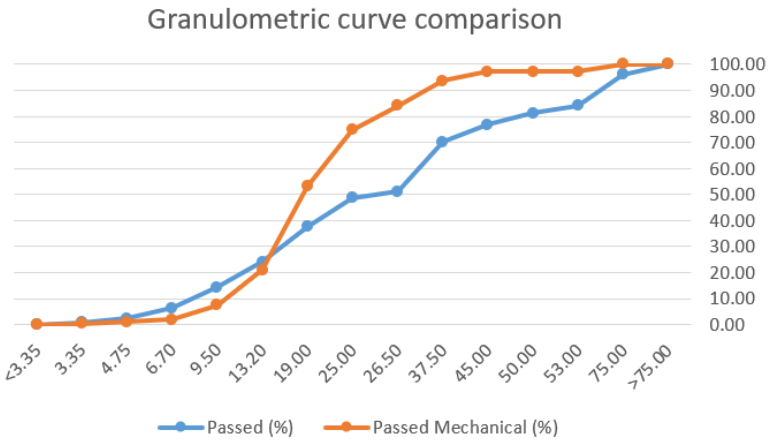
Comparison between the granulometric curves of the mechanical sieving and set 3 image 5 analysis



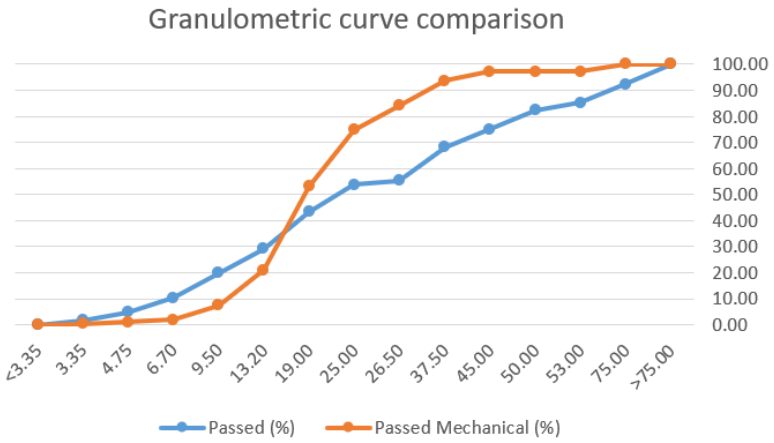
Comparison between the granulometric curves of the mechanical sieving and set 3 image 6 analysis



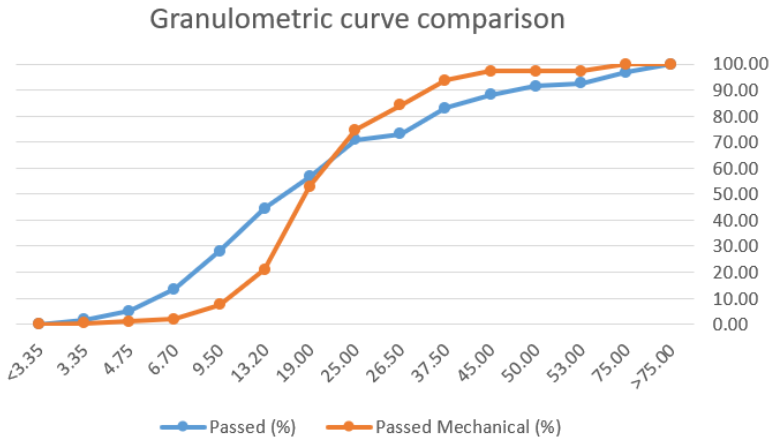
Comparison between the granulometric curves of the mechanical sieving and set 3 image 7 analysis



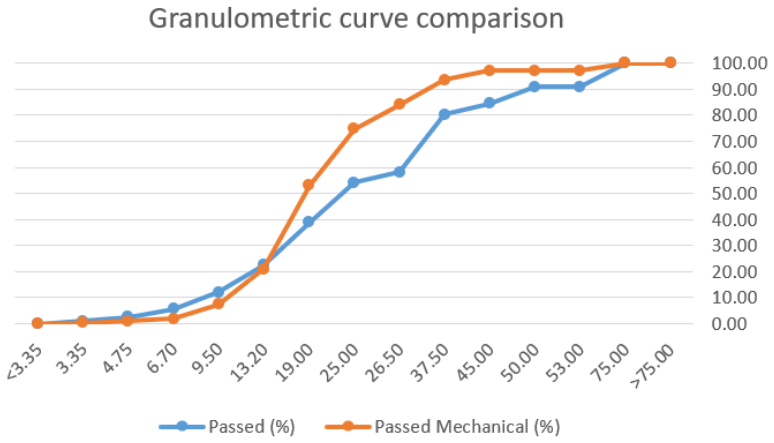
Comparison between the granulometric curves of the mechanical sieving and set 3 image 7 extra analysis



Comparison between the granulometric curves of the mechanical sieving and set 3 image 8 analysis

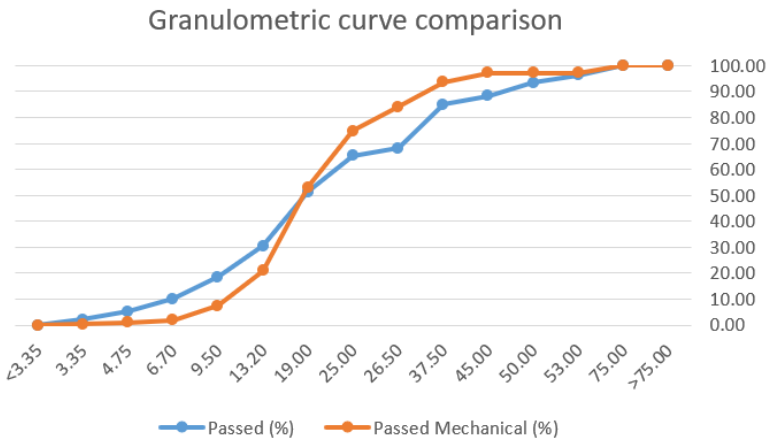


Comparison between the granulometric curves of the mechanical sieving and set 3 image 8 extra analysis

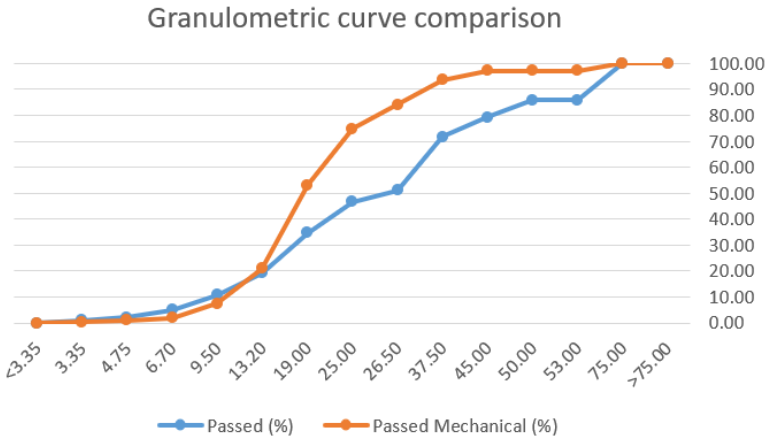


Comparison between the granulometric curves of the mechanical sieving and set 3 image 9 analysis

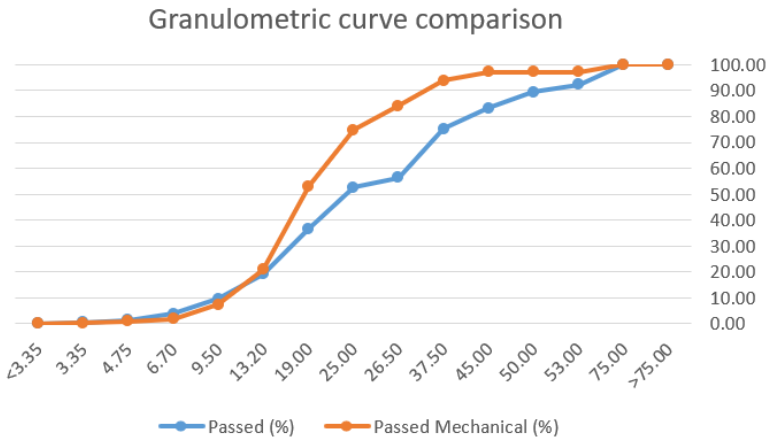
Set number 4



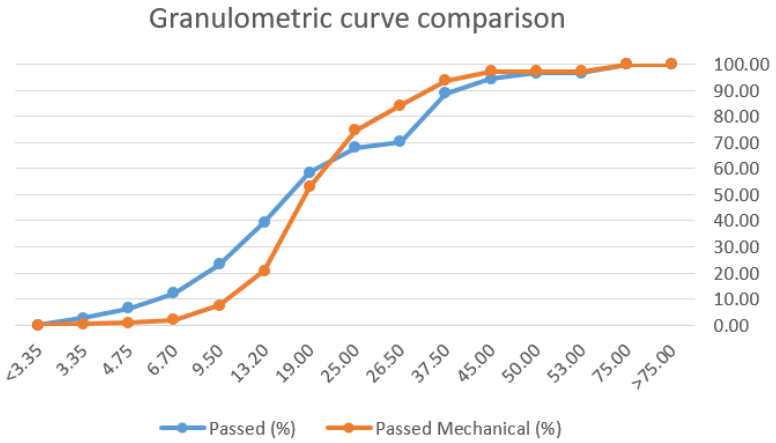
Comparison between the granulometric curves of the mechanical sieving and set 4 image 1 analysis



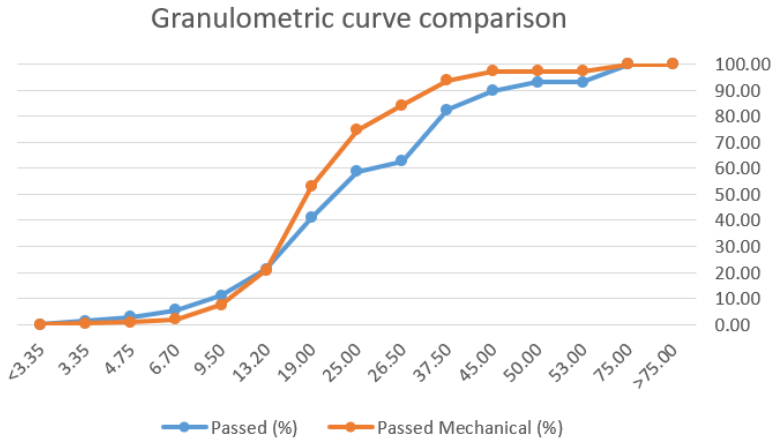
Comparison between the granulometric curves of the mechanical sieving and set 4 image 2 analysis



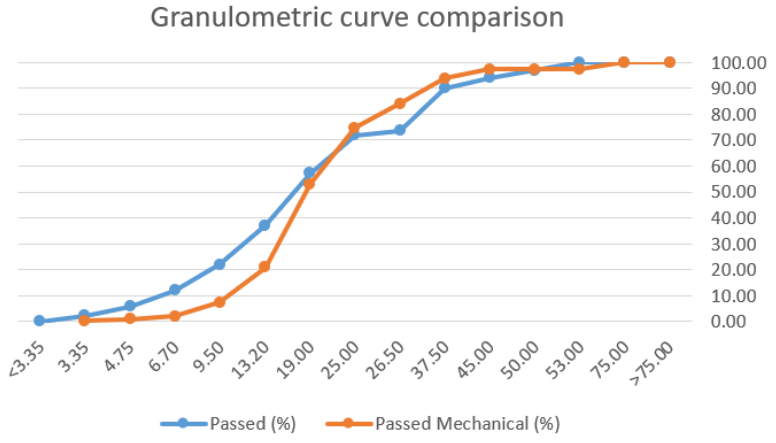
Comparison between the granulometric curves of the mechanical sieving and set 4 image 3 analysis



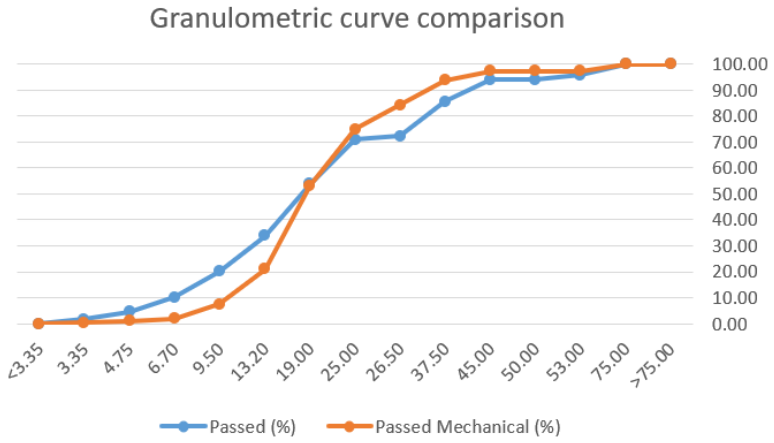
Comparison between the granulometric curves of the mechanical sieving and set 4 image 4 analysis



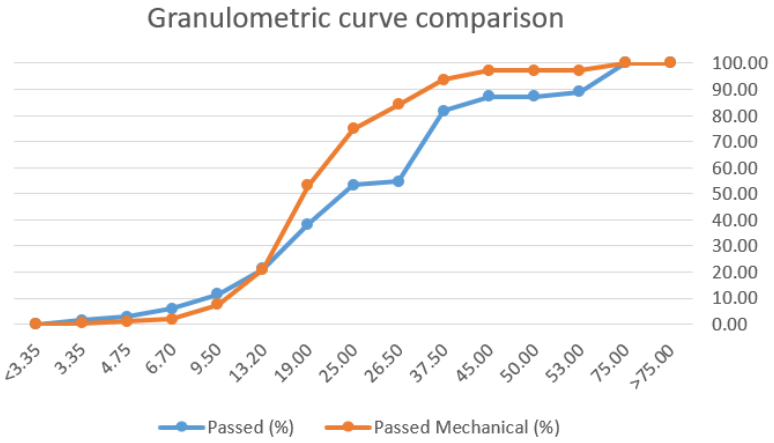
Comparison between the granulometric curves of the mechanical sieving and set 4 image 5 analysis



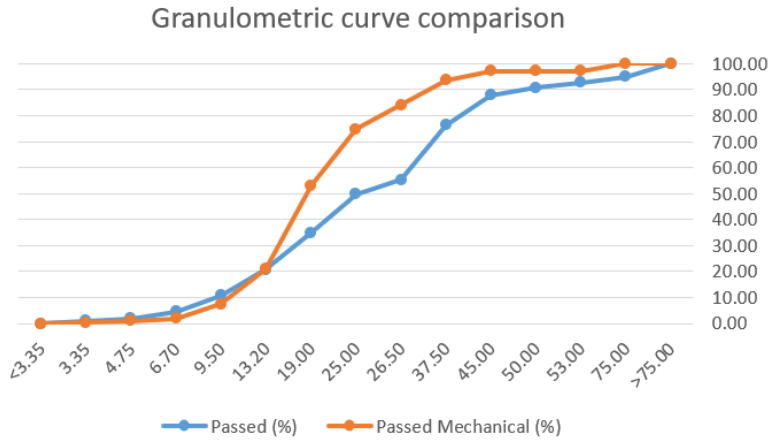
Comparison between the granulometric curves of the mechanical sieving and set 4 image 6 analysis



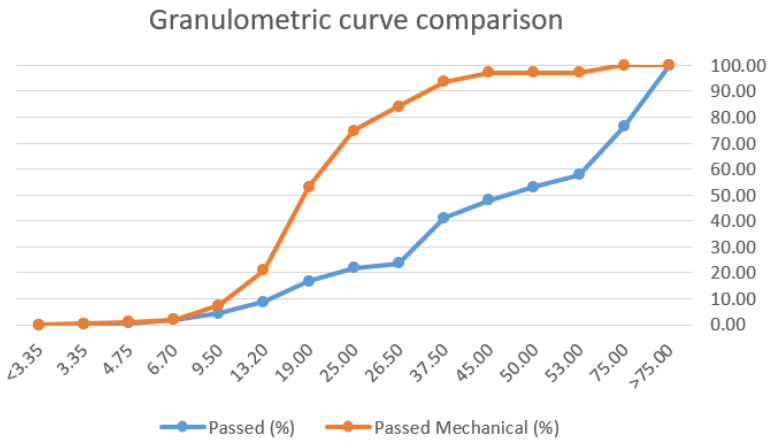
Comparison between the granulometric curves of the mechanical sieving and set 4 image 7 analysis



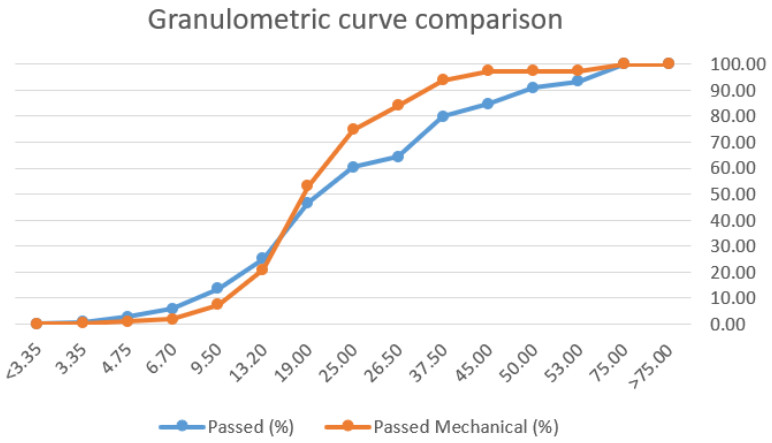
Comparison between the granulometric curves of the mechanical sieving and set 4 image 8 analysis



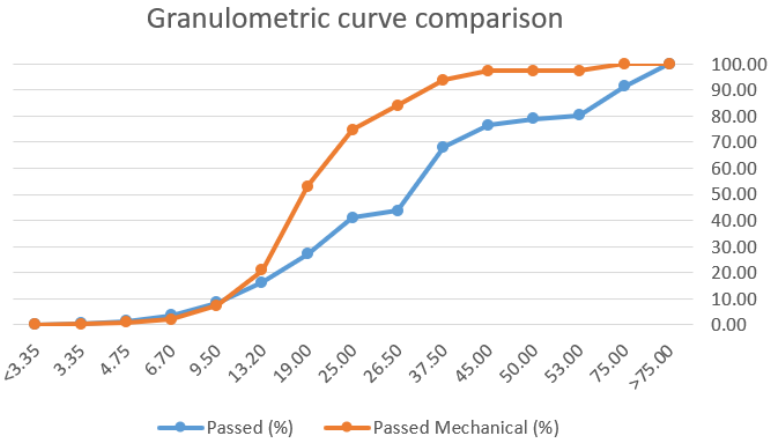
Comparison between the granulometric curves of the mechanical sieving and set 4 image 9 analysis



Comparison between the granulometric curves of the mechanical sieving and set 4 image 10 analysis

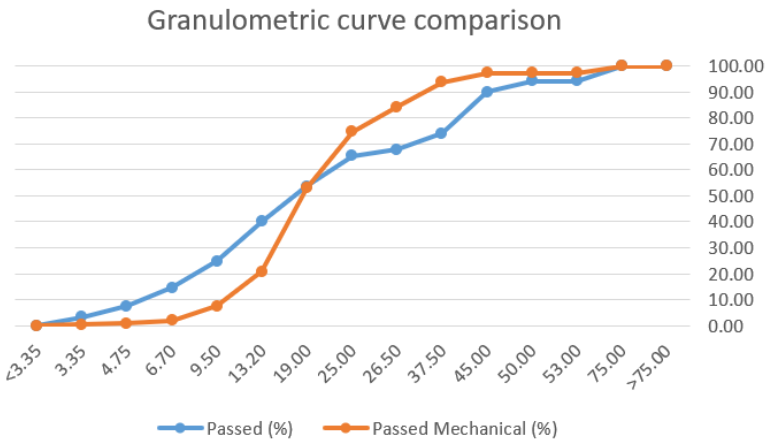


Comparison between the granulometric curves of the mechanical sieving and set 4 image 11 analysis

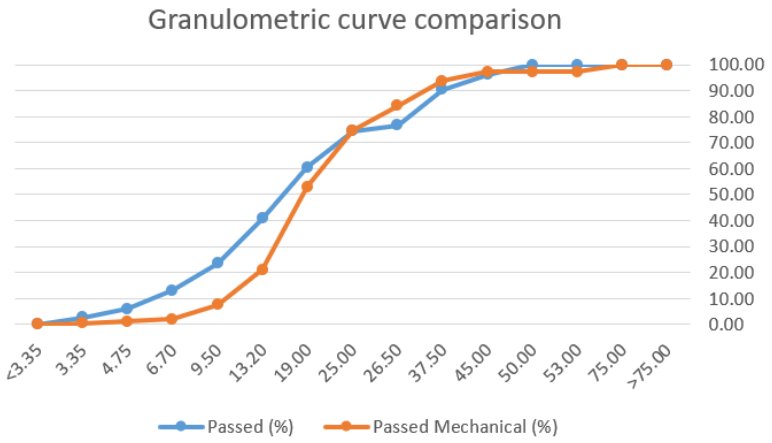


Comparison between the granulometric curves of the mechanical sieving and set 4 image 12 analysis

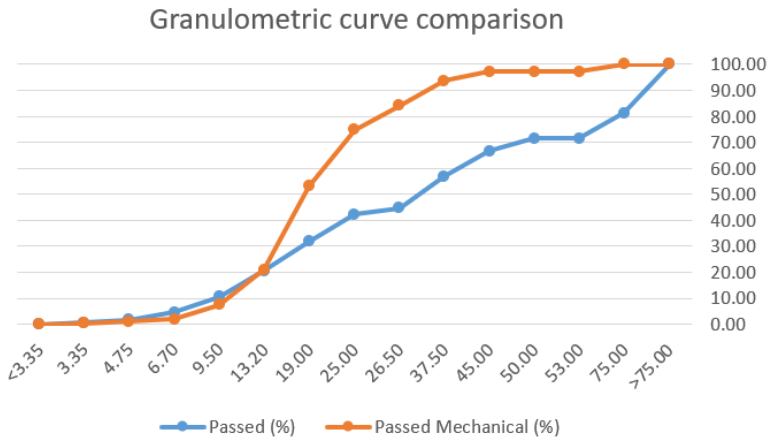
Set number 5



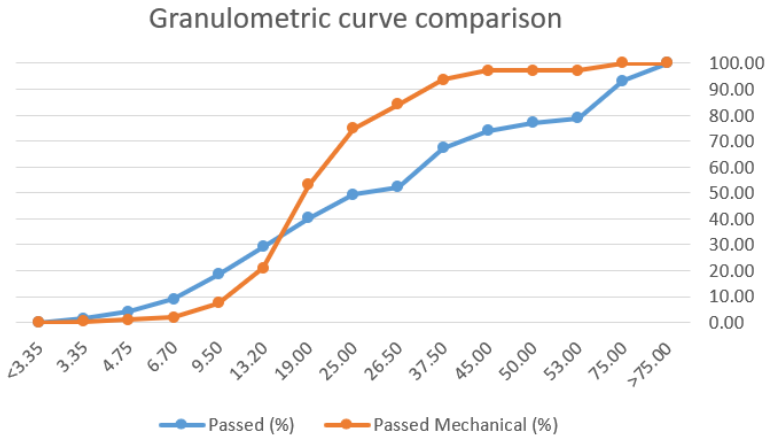
Comparison between the granulometric curves of the mechanical sieving and set 5 image 1 analysis



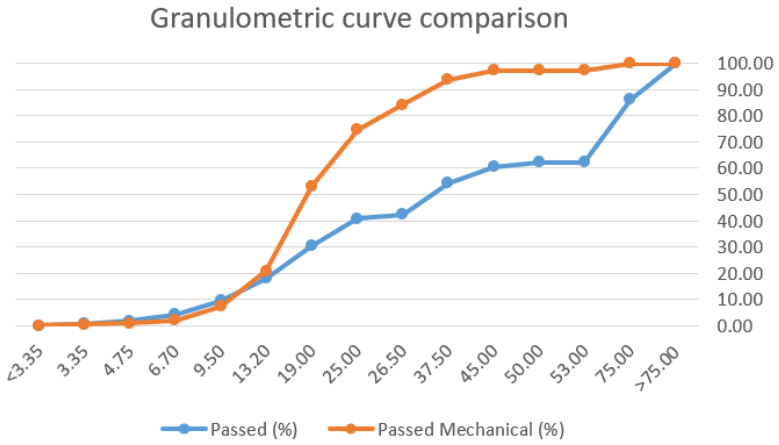
Comparison between the granulometric curves of the mechanical sieving and set 5 image 2 analysis



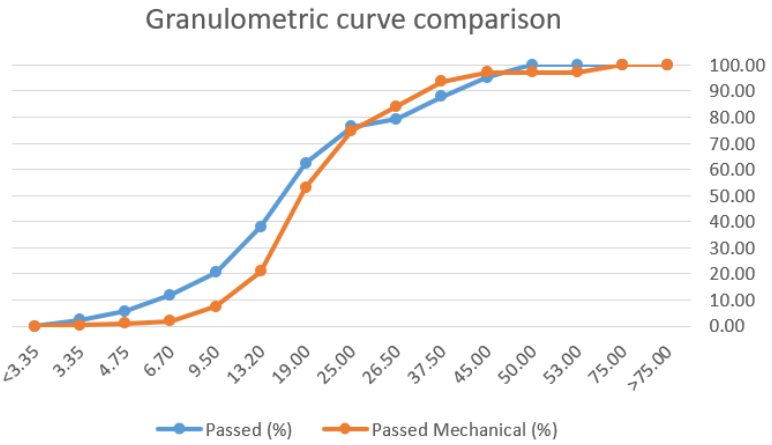
Comparison between the granulometric curves of the mechanical sieving and set 5 image 3 analysis



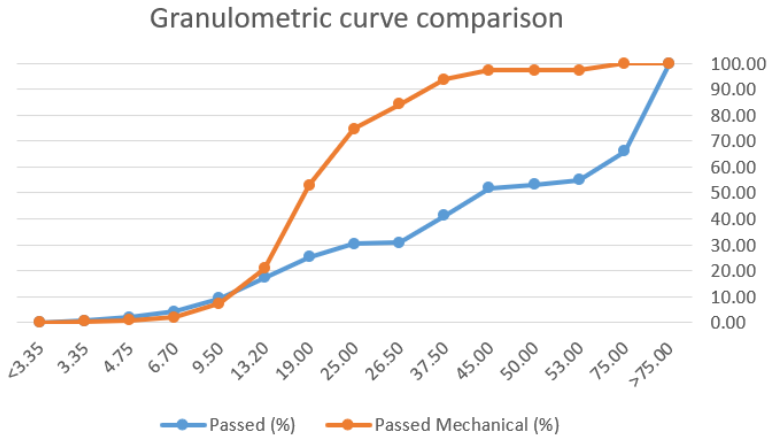
Comparison between the granulometric curves of the mechanical sieving and set 5 image 4 analysis



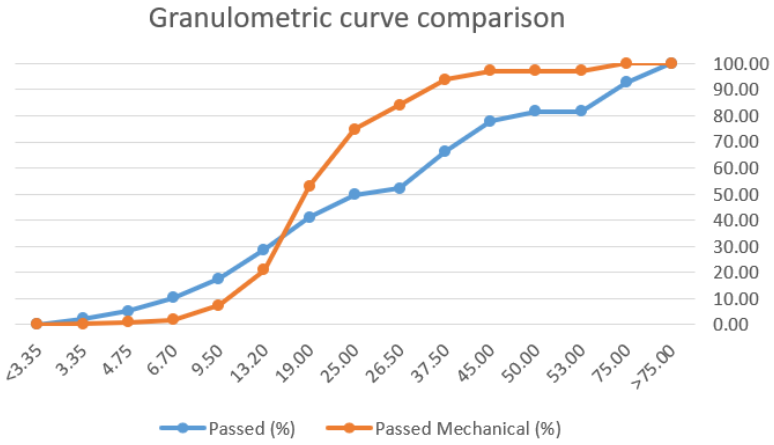
Comparison between the granulometric curves of the mechanical sieving and set 5 image 5 analysis



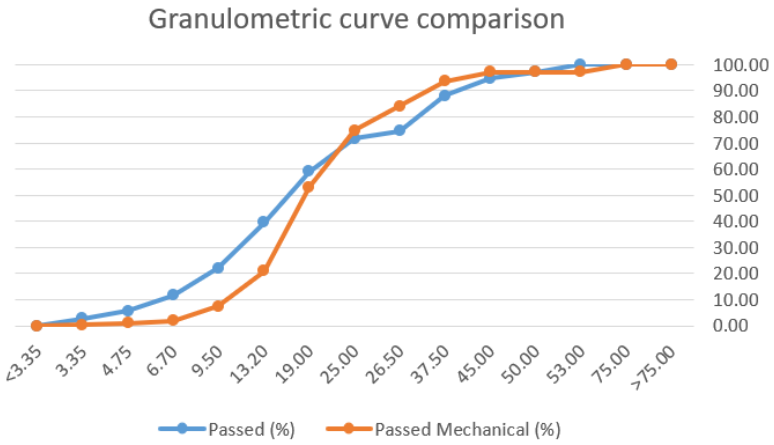
Comparison between the granulometric curves of the mechanical sieving and set 5 image 6 analysis



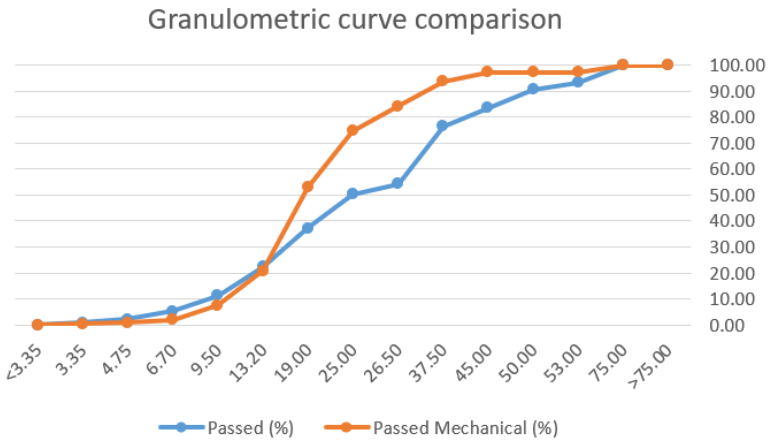
Comparison between the granulometric curves of the mechanical sieving and set 5 image 7 analysis



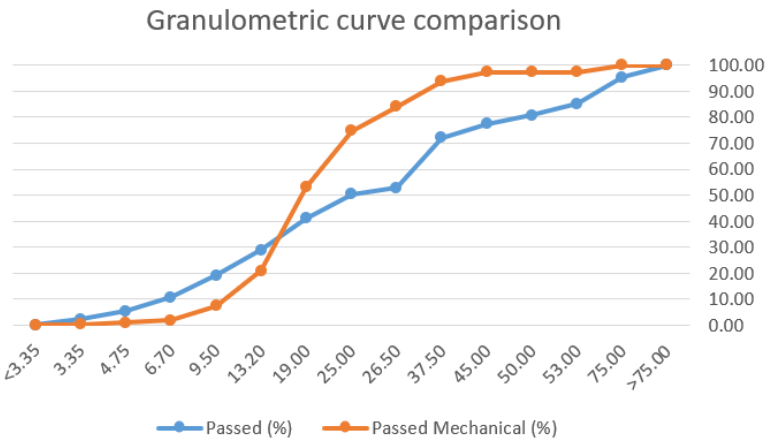
Comparison between the granulometric curves of the mechanical sieving and set 5 image 8 analysis



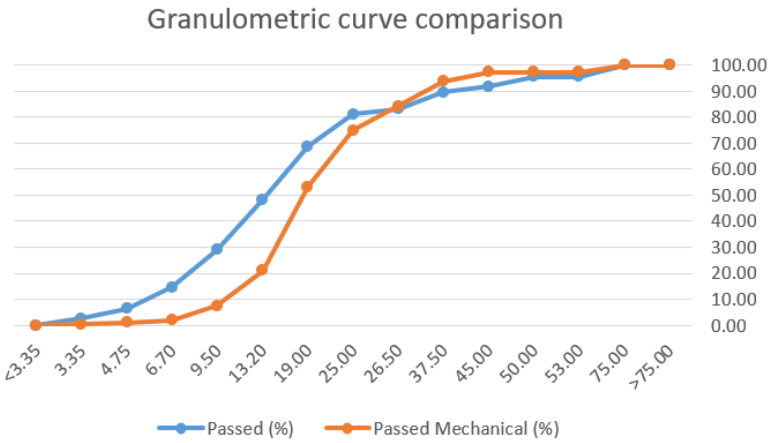
Comparison between the granulometric curves of the mechanical sieving and set 5 image 9 analysis



Comparison between the granulometric curves of the mechanical sieving and set 5 image 10 analysis



Comparison between the granulometric curves of the mechanical sieving and set 5 image 11 analysis



Comparison between the granulometric curves of the mechanical sieving and set 5 image 12 analysis

Appendix II

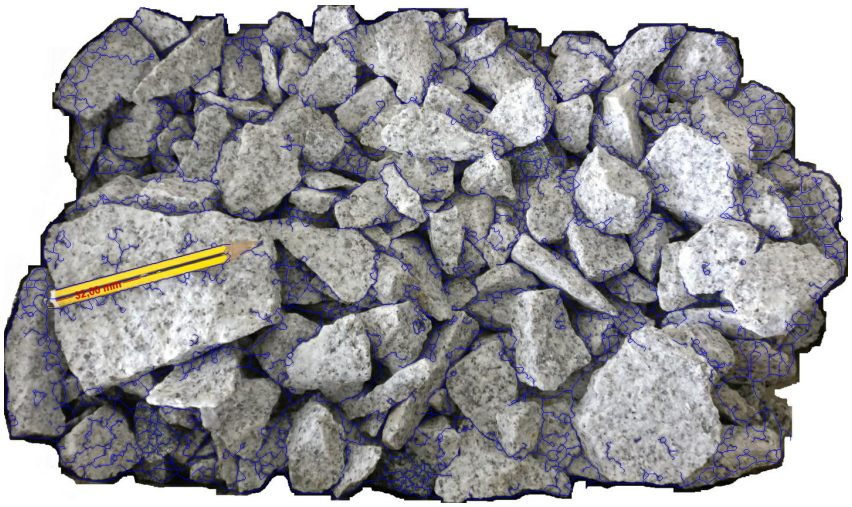
Test trial 1

Test trial 1 image 1

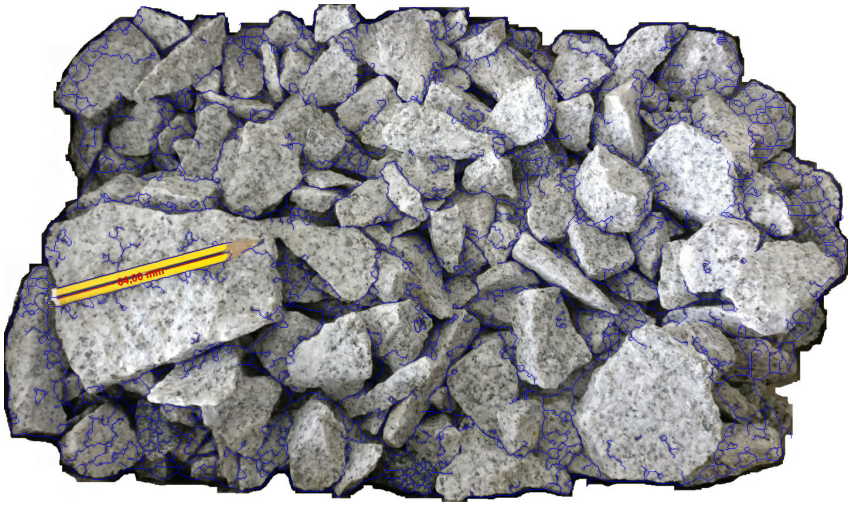
Test trial 1 image 2

Test trial 2

Test trial 2 image 1



Test trial 2 image 2

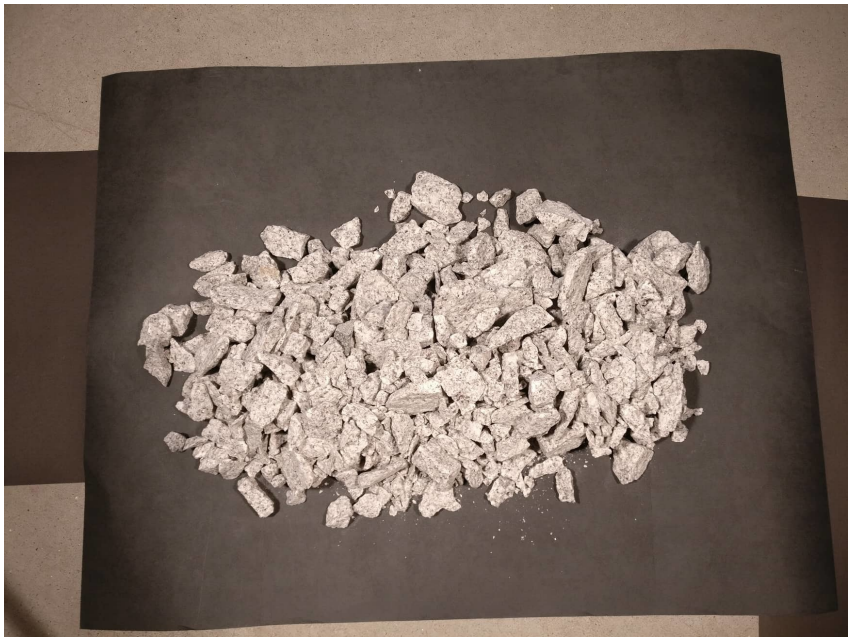


Test trial 2 image 3

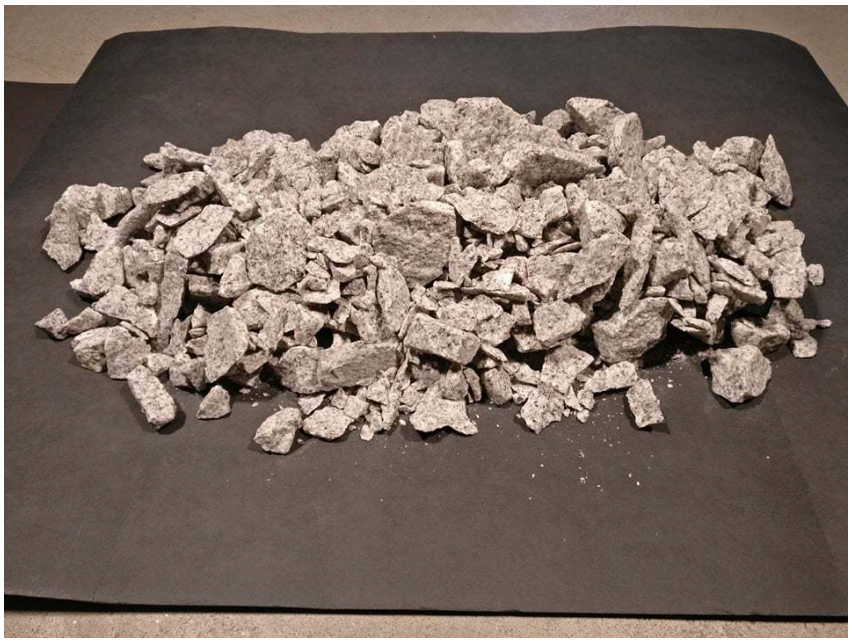
Test trial 2 image 4

Test trial 2 image 5

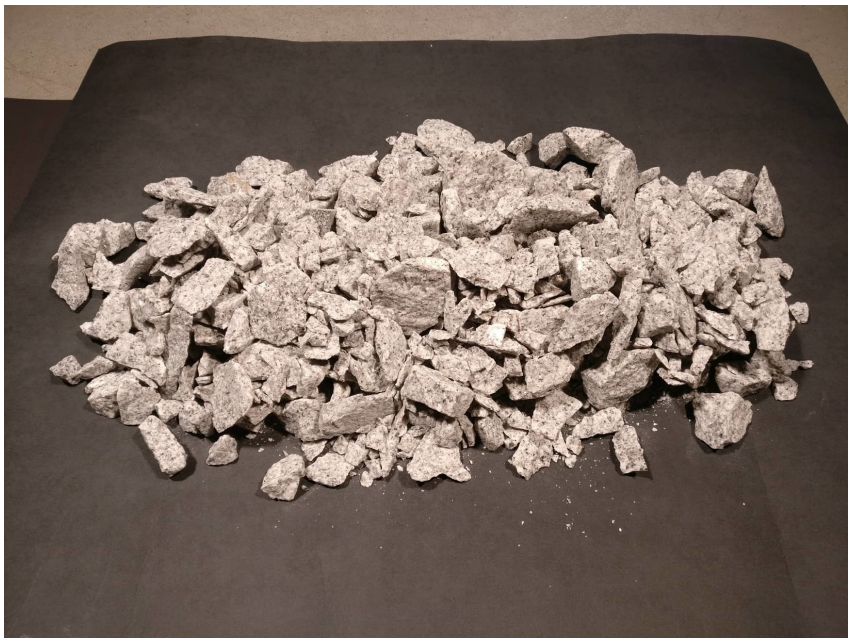
Set number 1



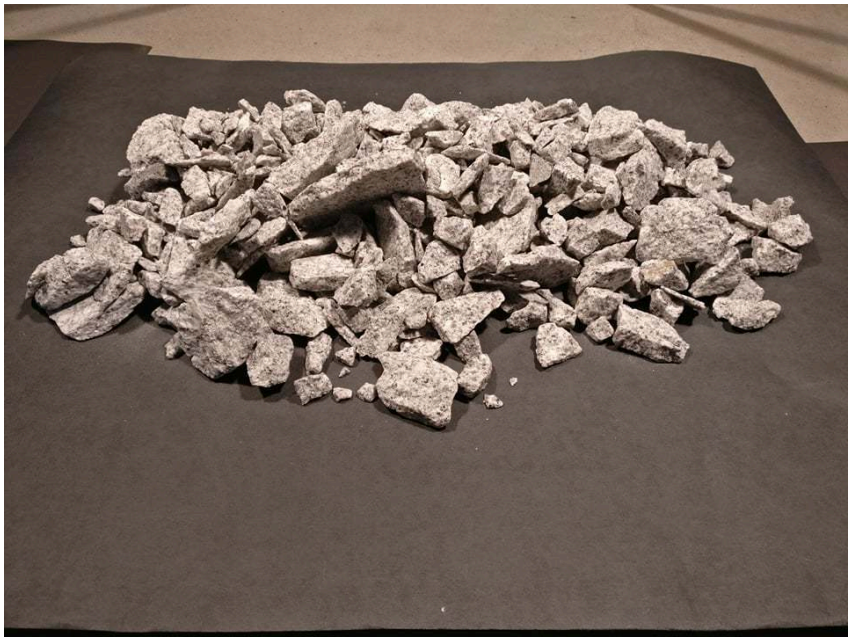
Set number 1 image 1



Set number 1 image 2



Set number 1 image 3



Set number 1 image 4

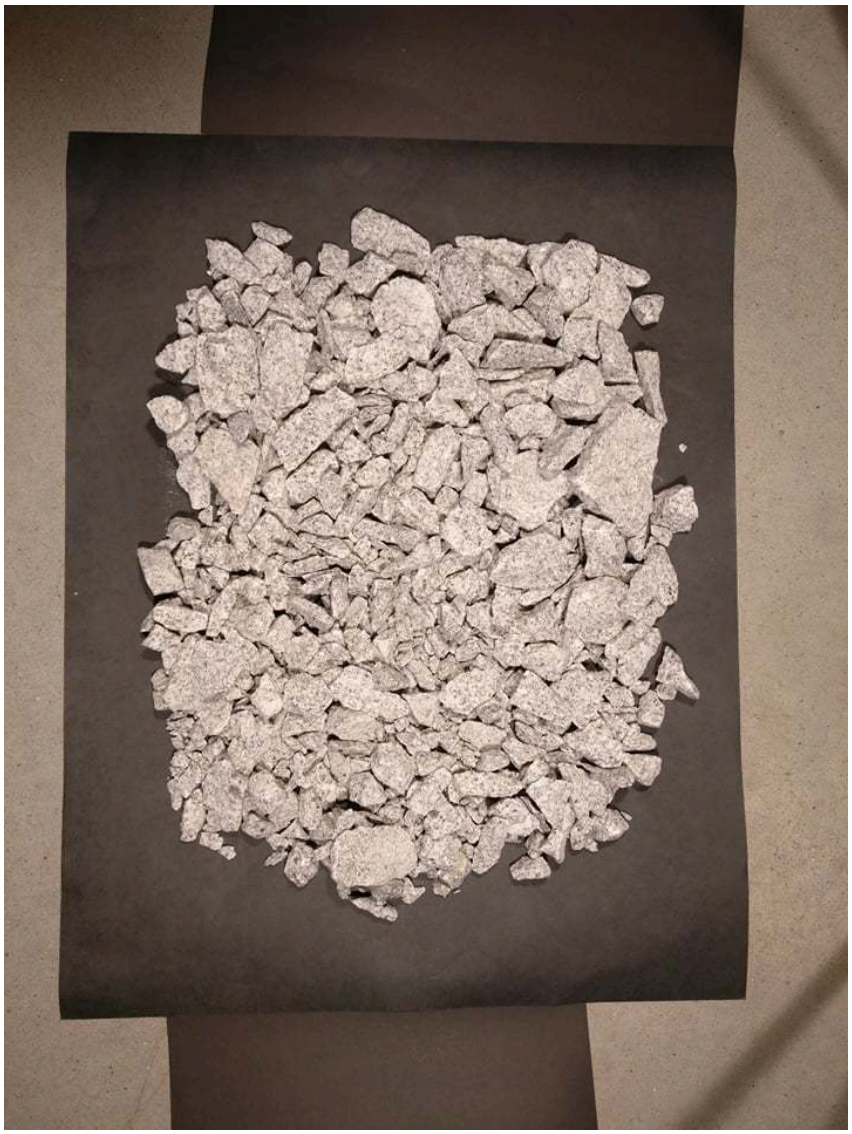
Set number 1 image 5

Set number 1 image 6

Set number 1 image 7

Set number 2

Set number 2 image 1

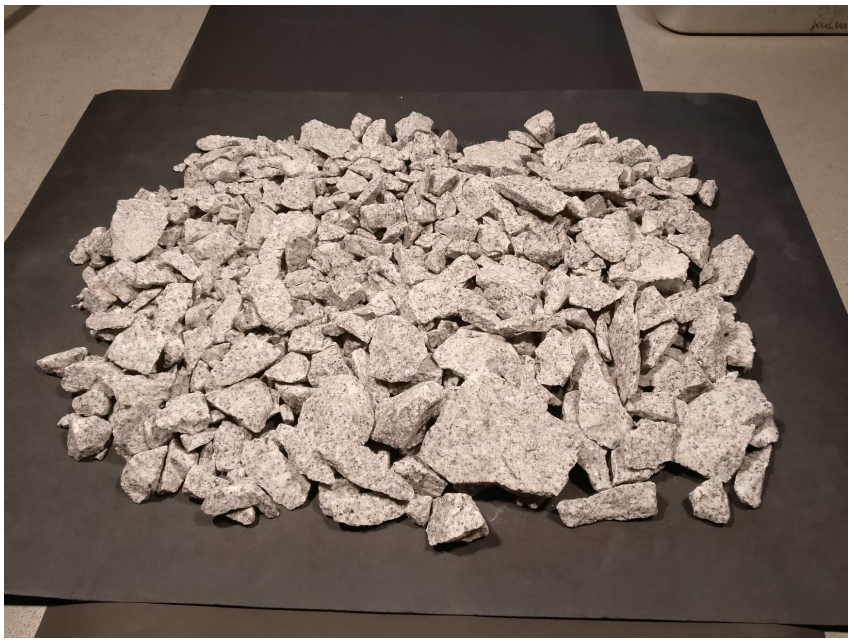


Set number 2 image 2

Set number 2 image 3

Set number 2 image 4

Set number 2 image 5



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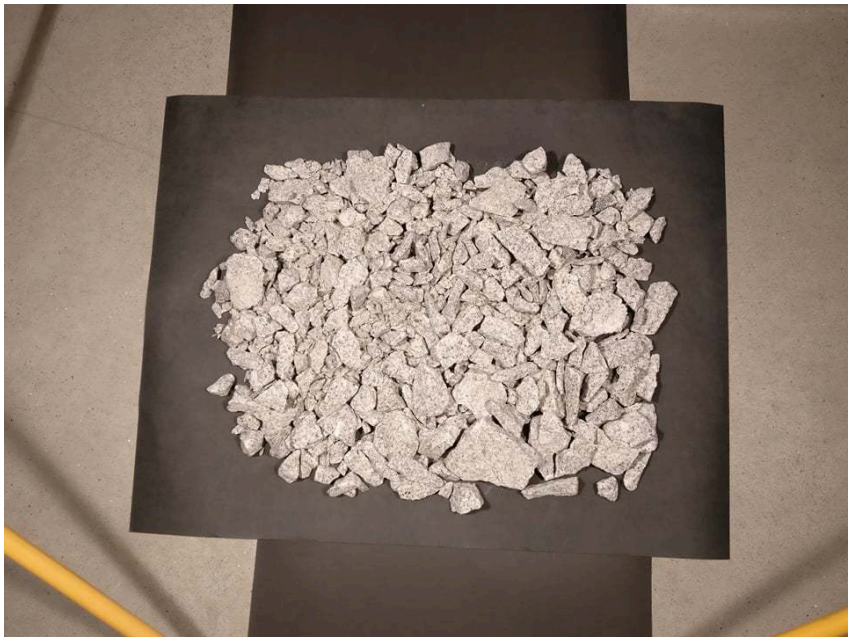
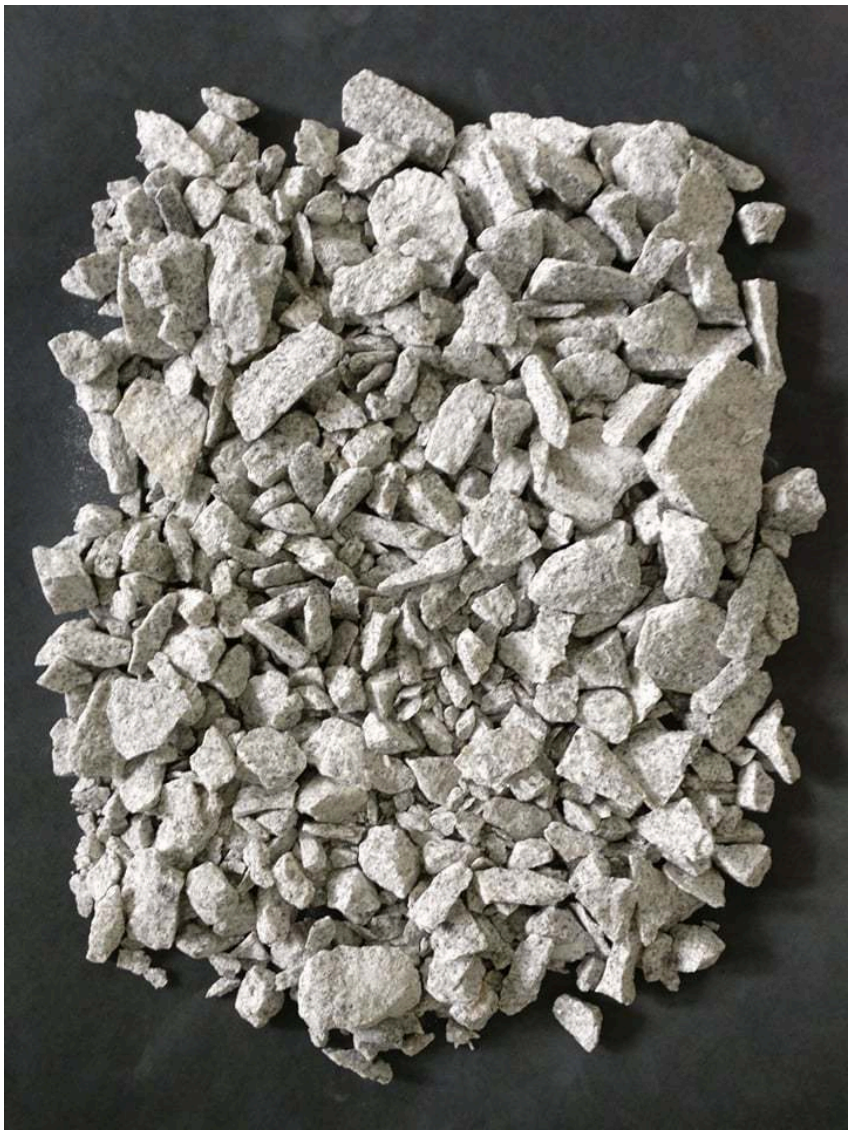


Set number 2 image 7

Set number 2 image 8

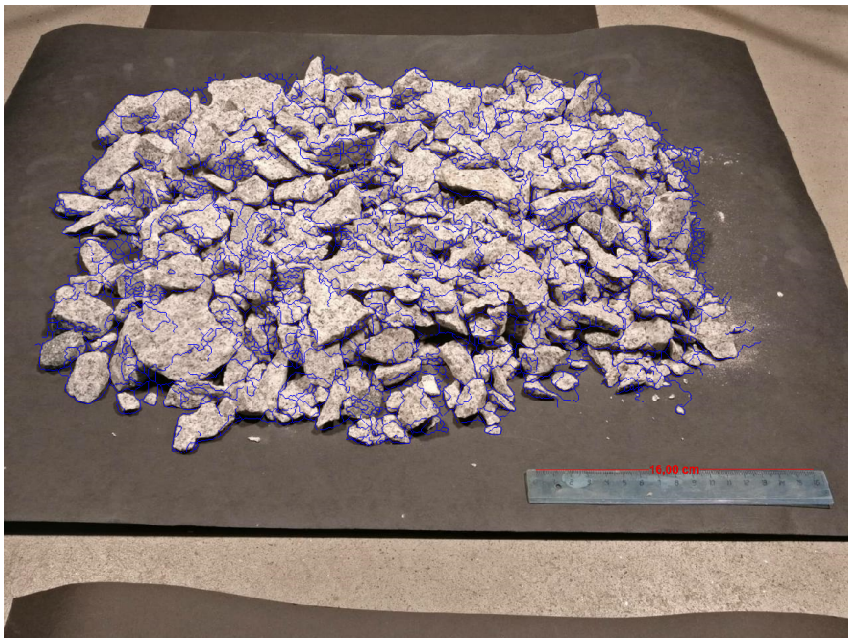
Set number 2 image 9



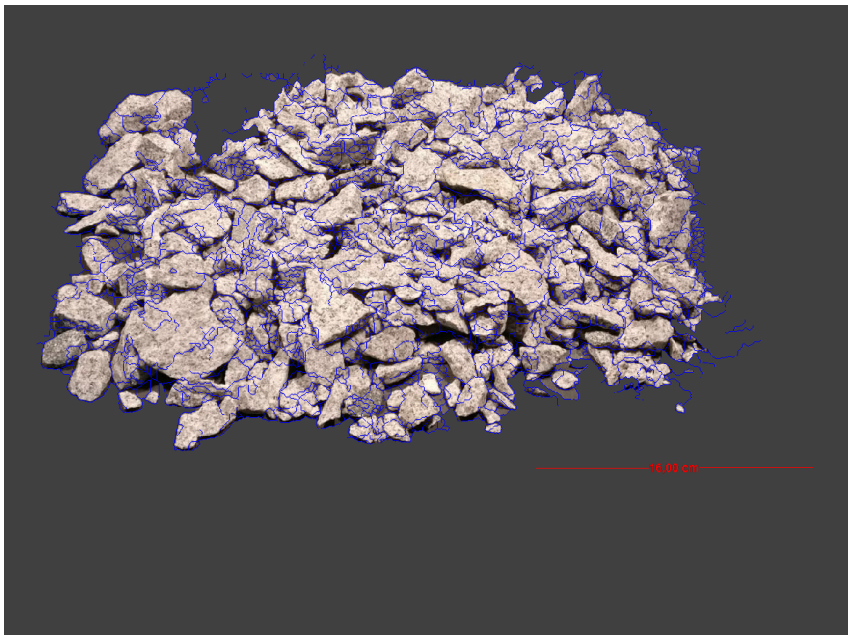
Set number 2 image 10

Set number 2 image 11

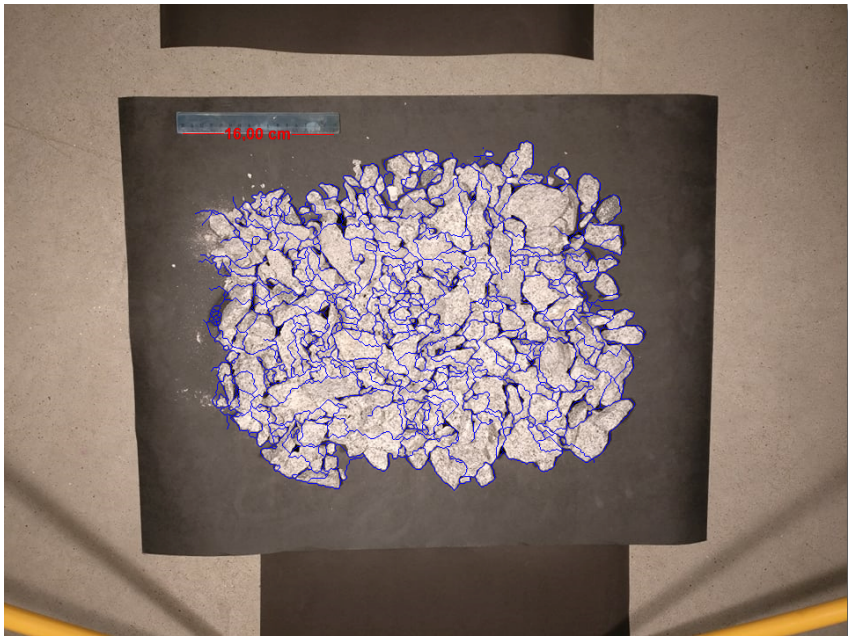
Set number 3



Set number 3 image 1 without background removal



Set number 3 image 1 with background removal



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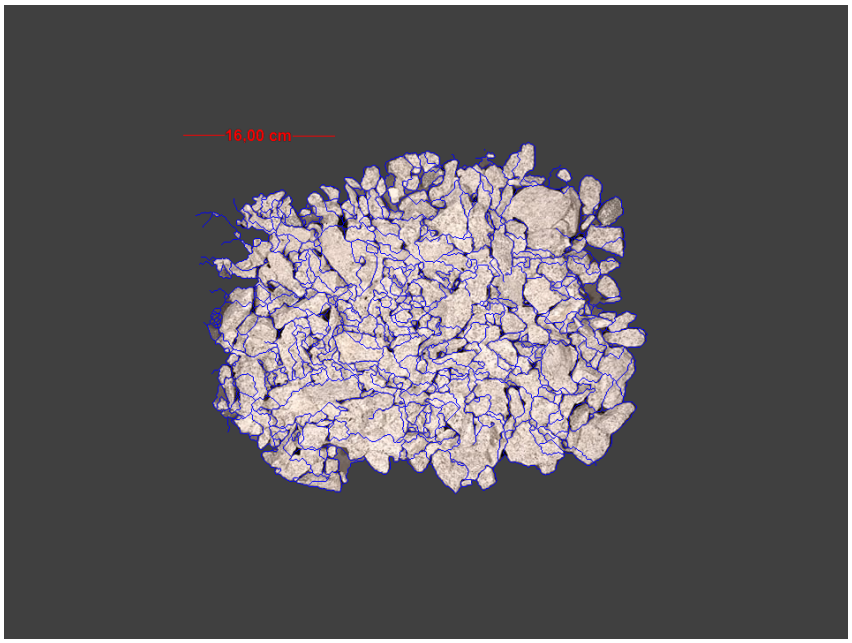

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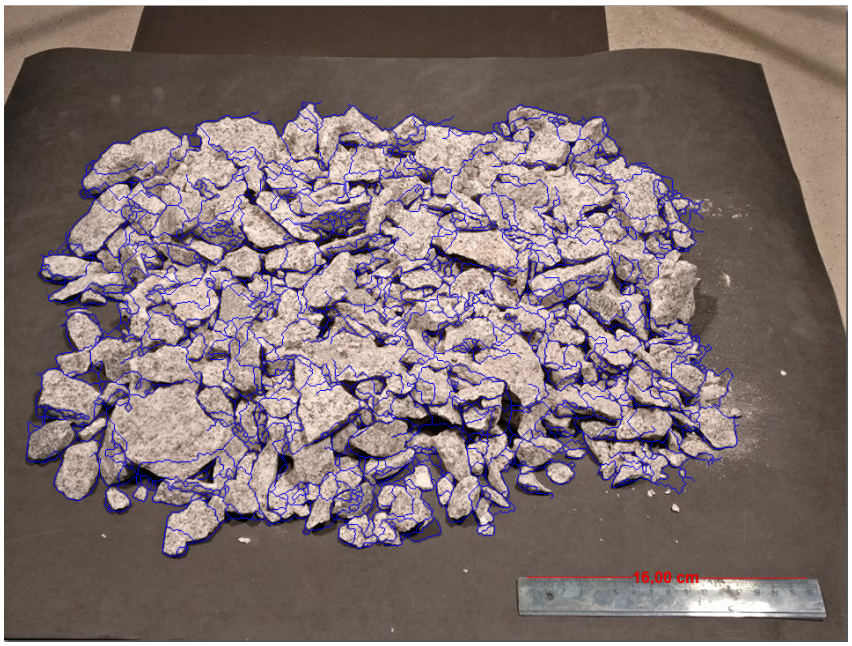
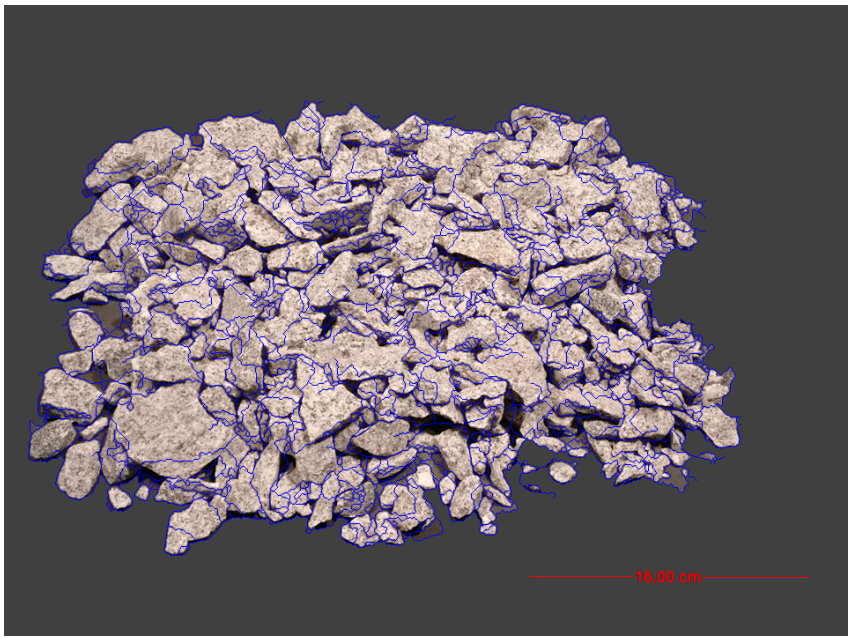


Set number 3 image 3 without background removal



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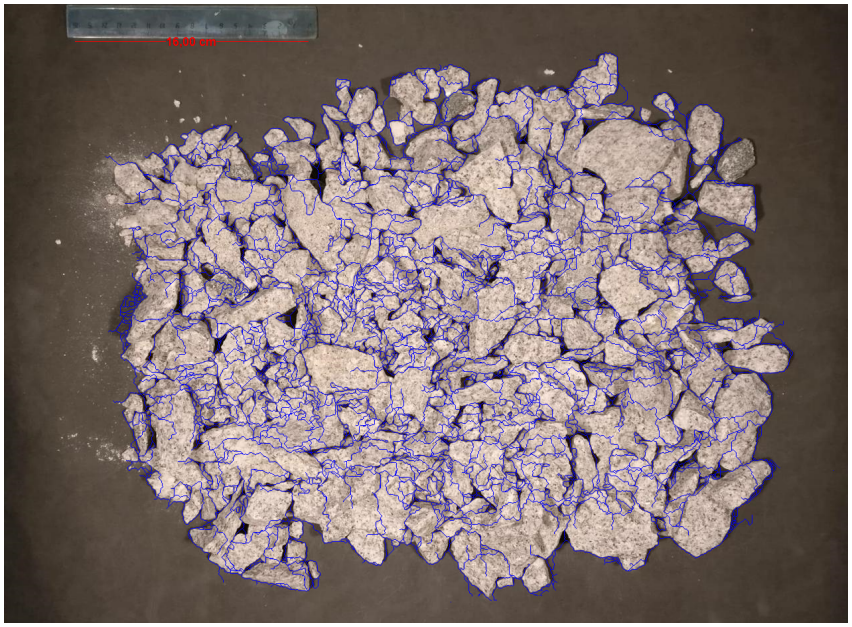

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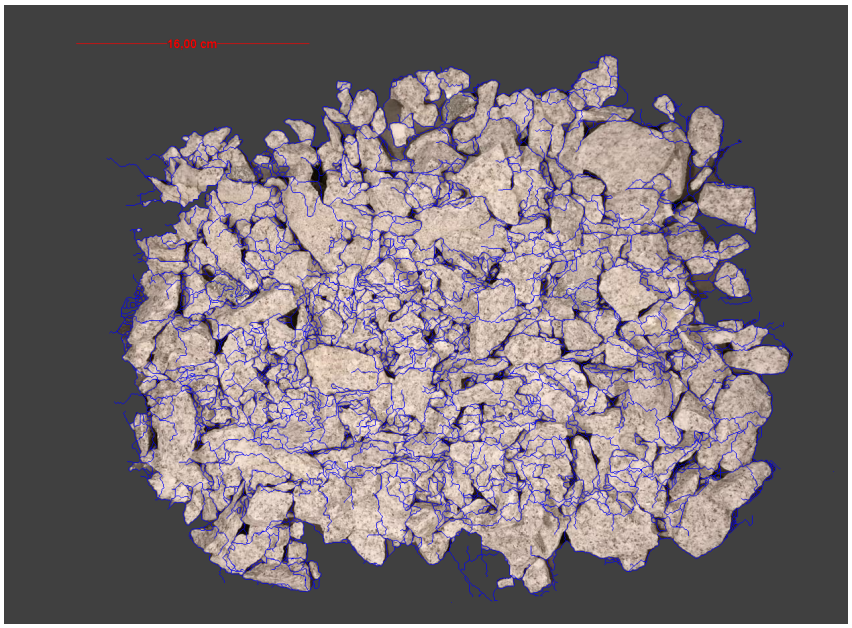

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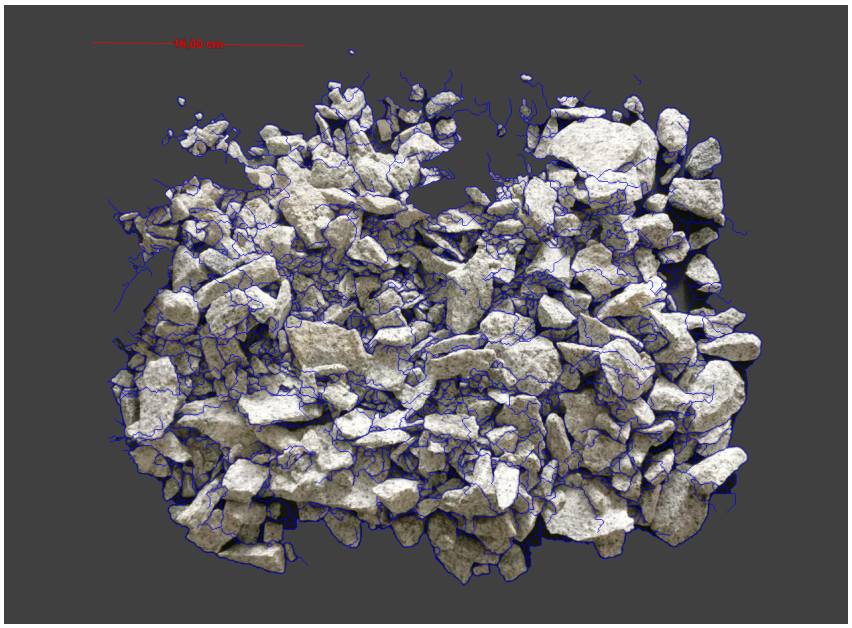

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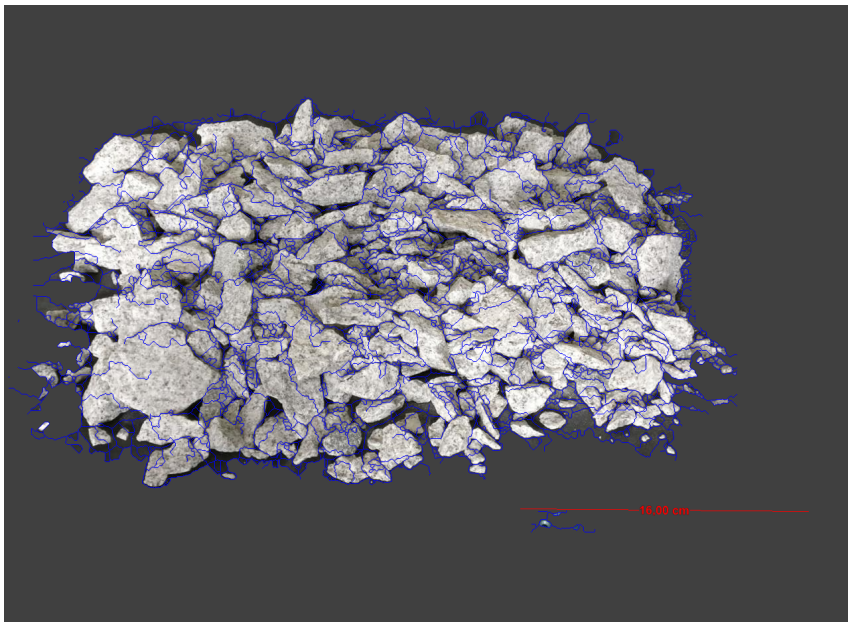

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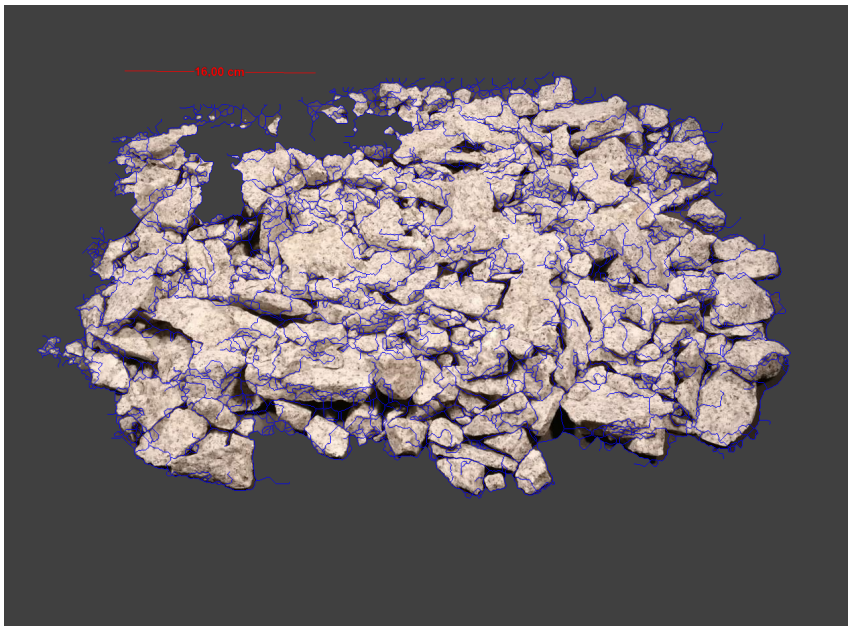

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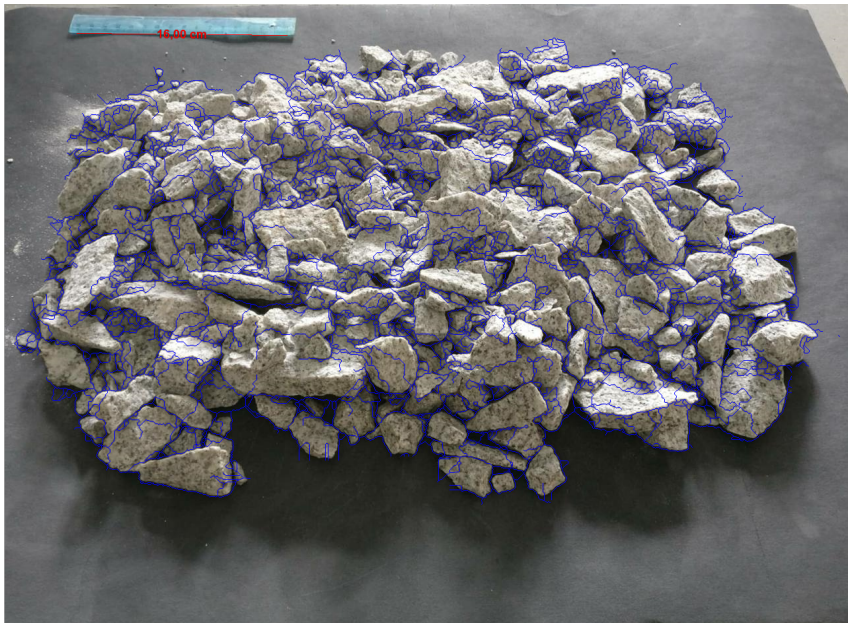

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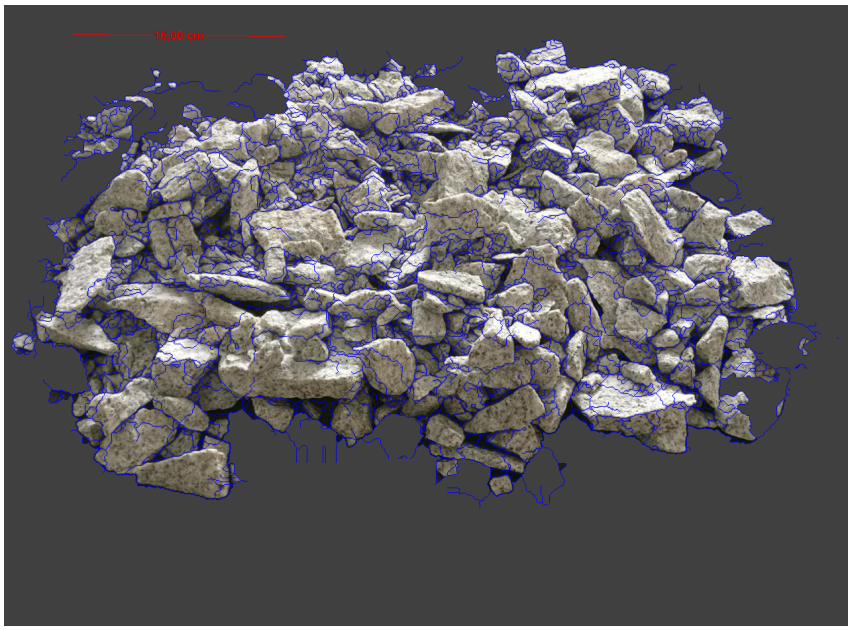

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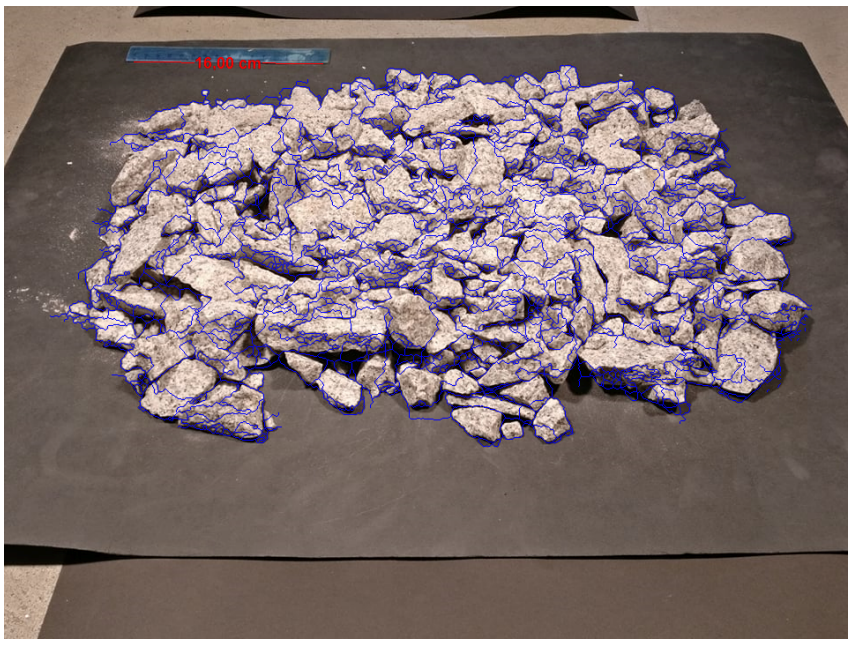

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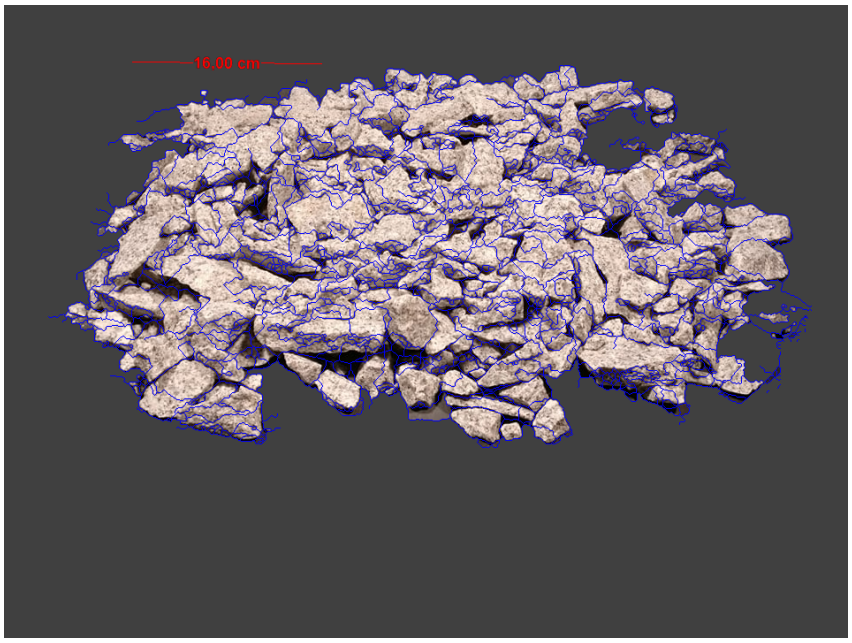

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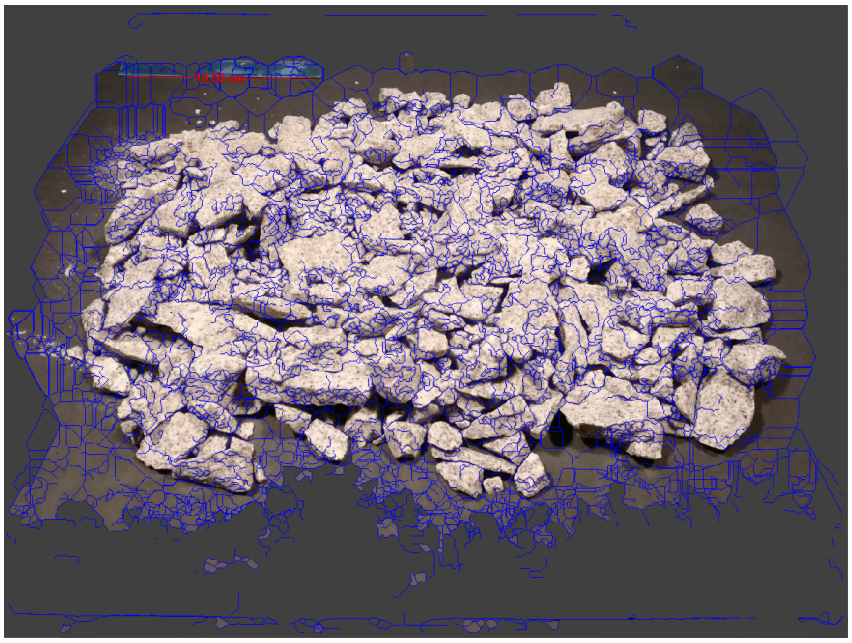

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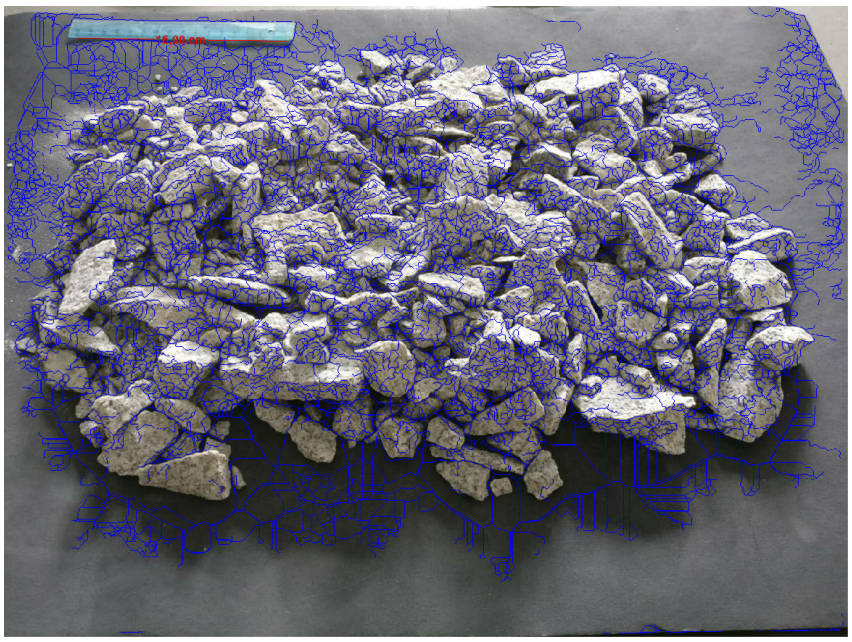

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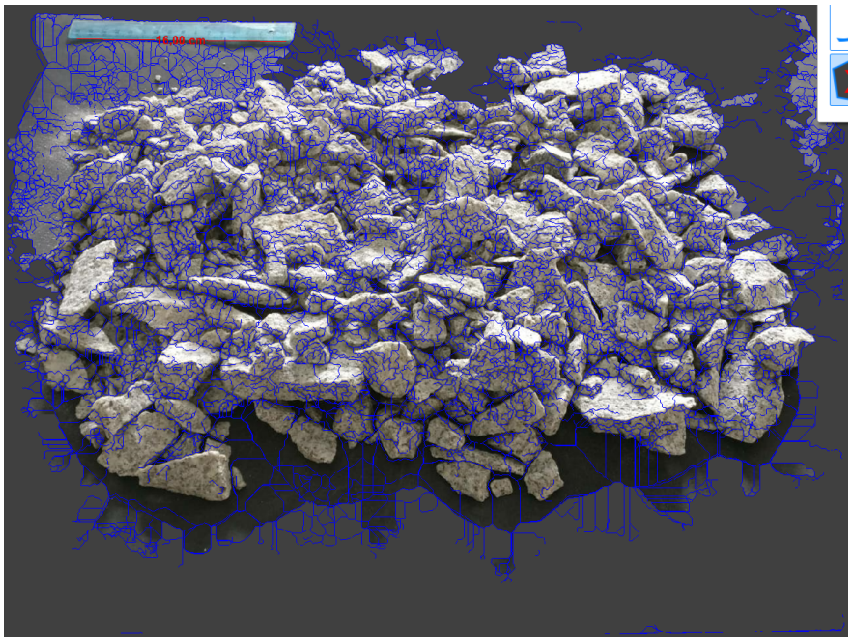

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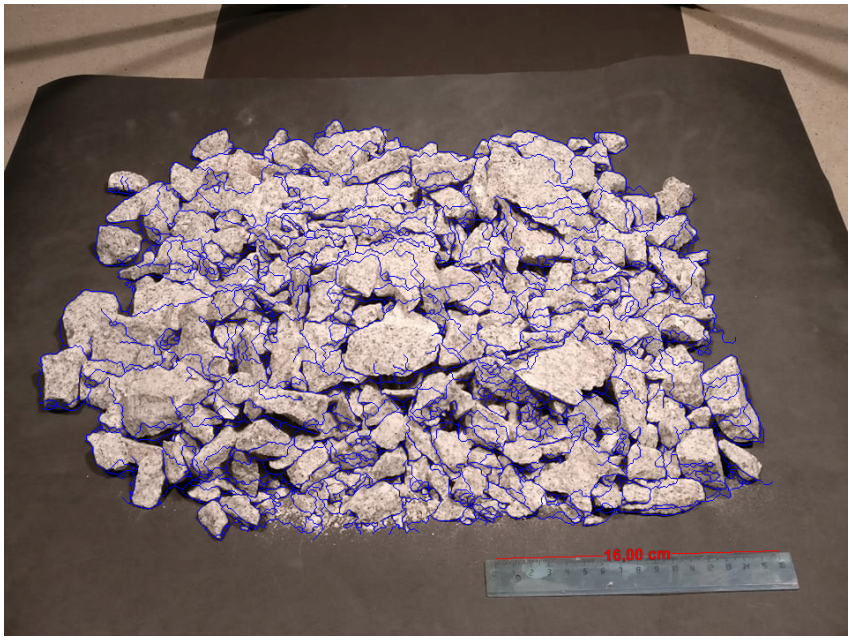

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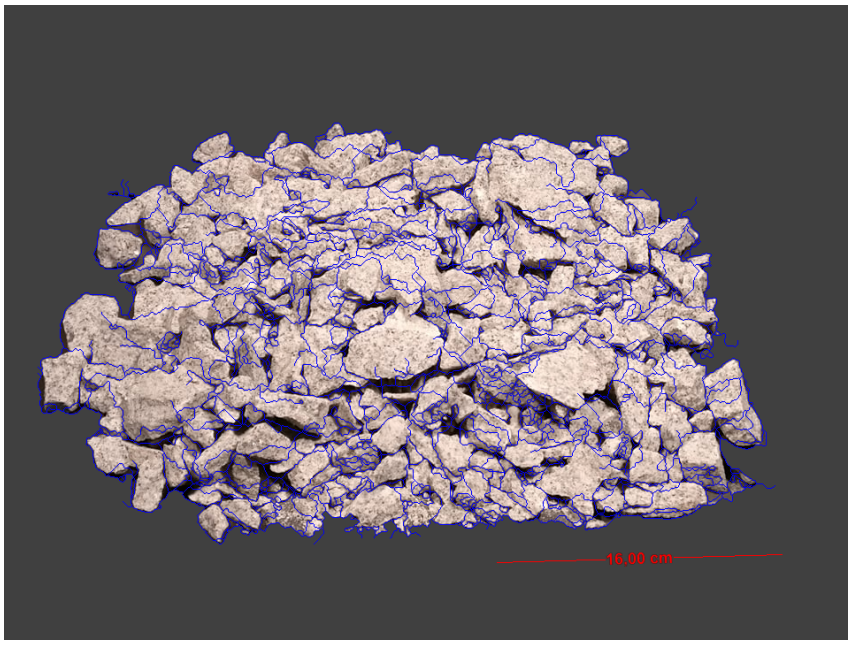

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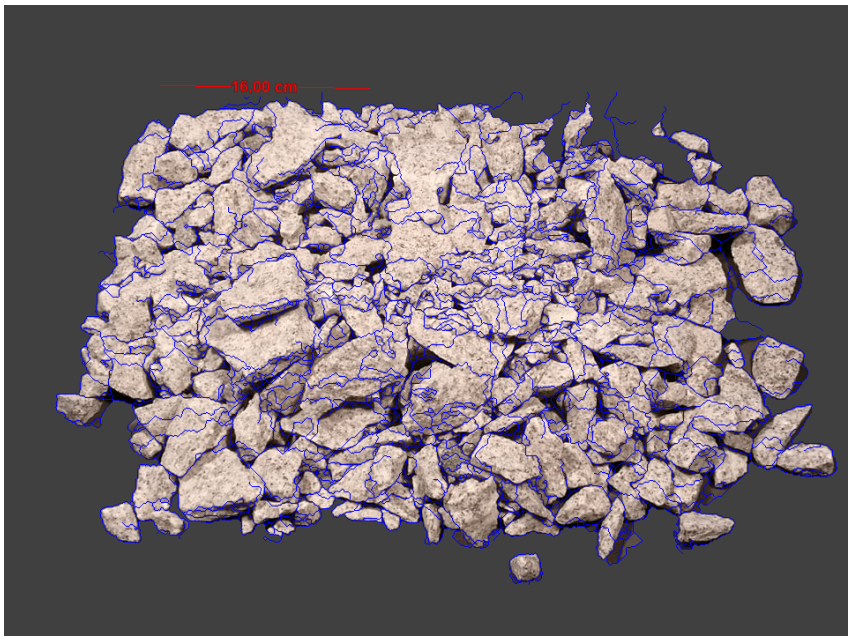

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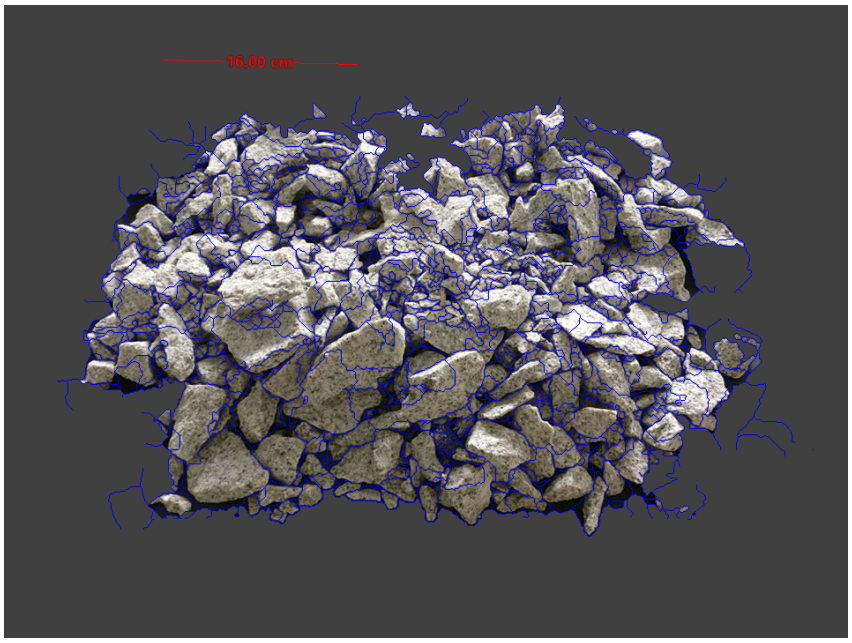

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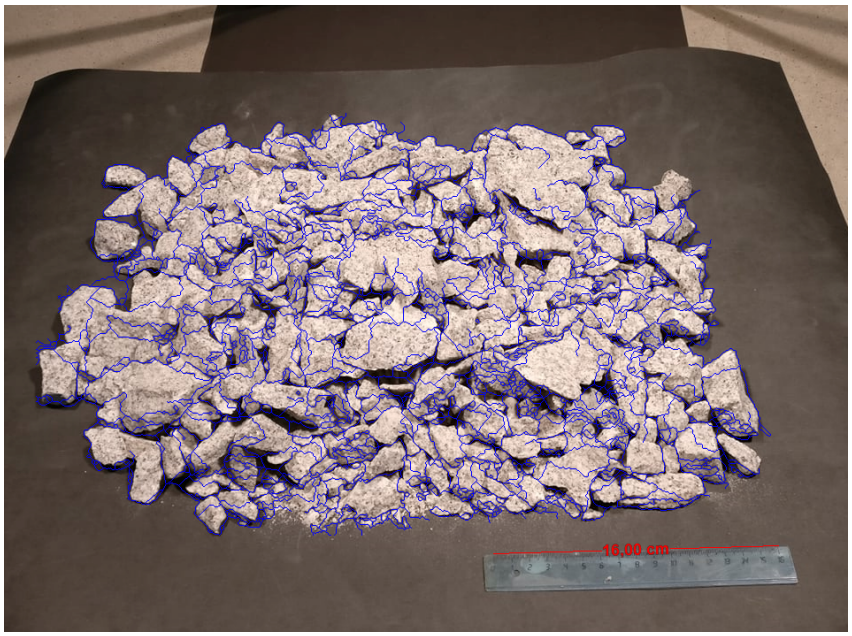

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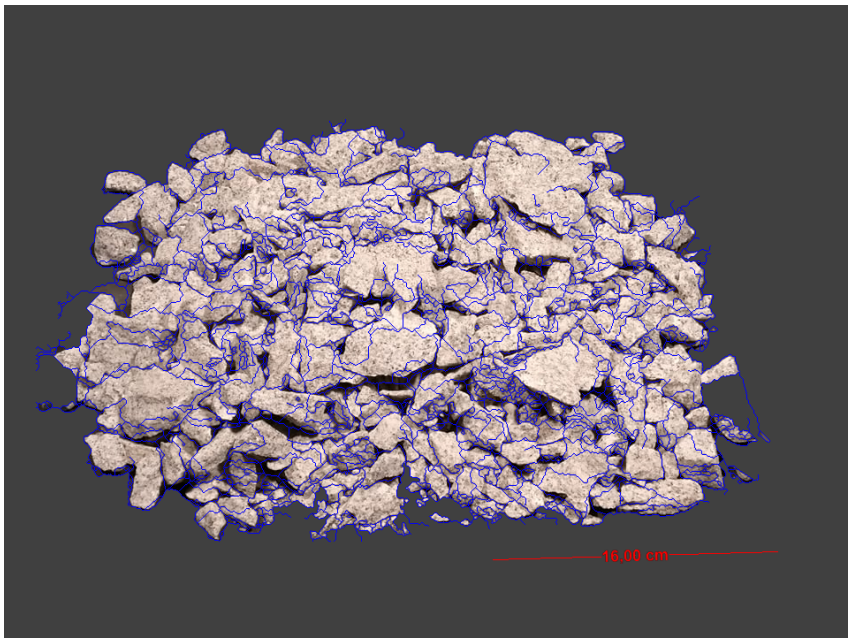

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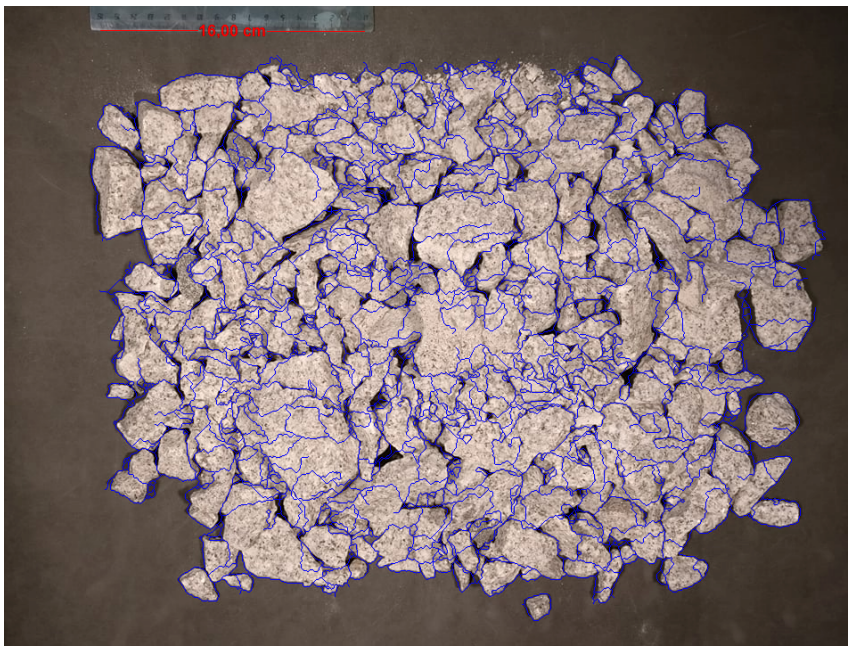

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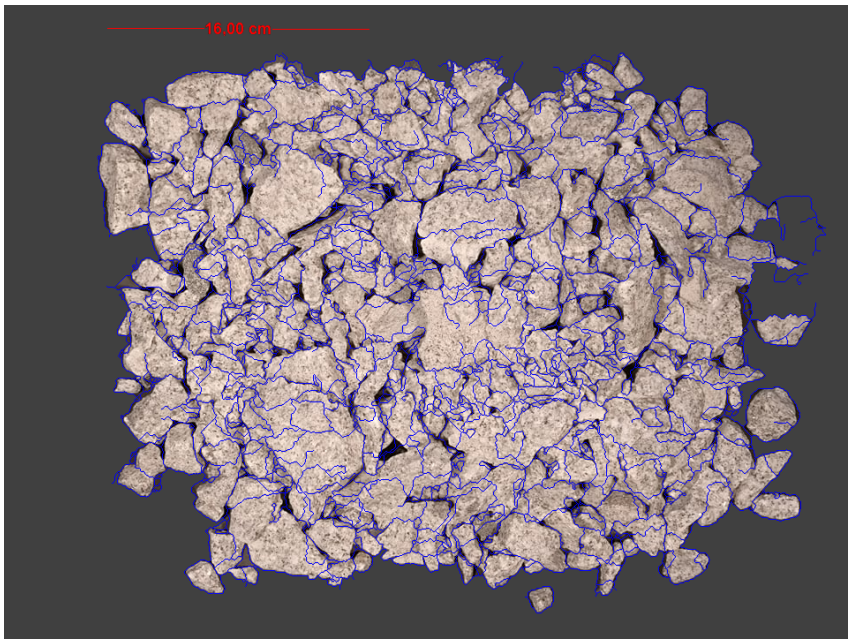

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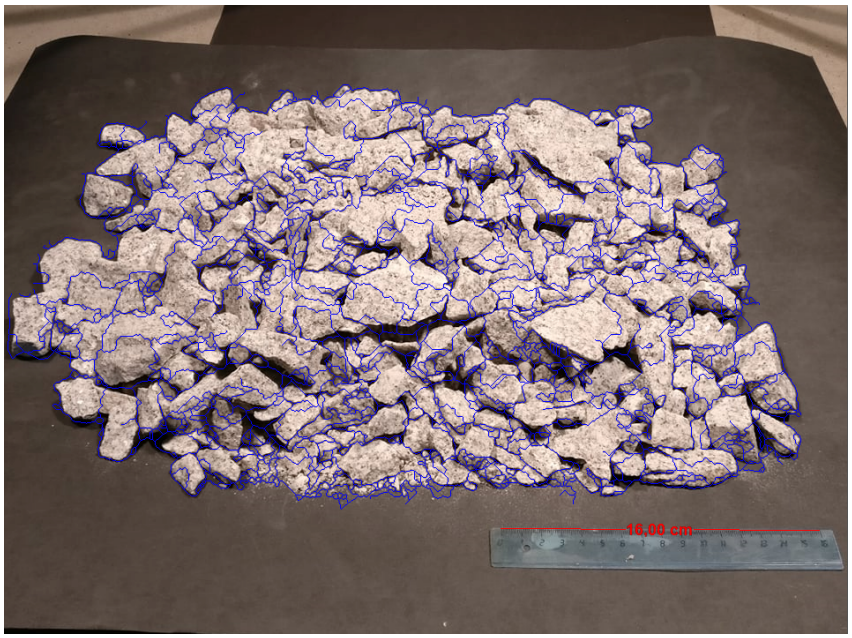

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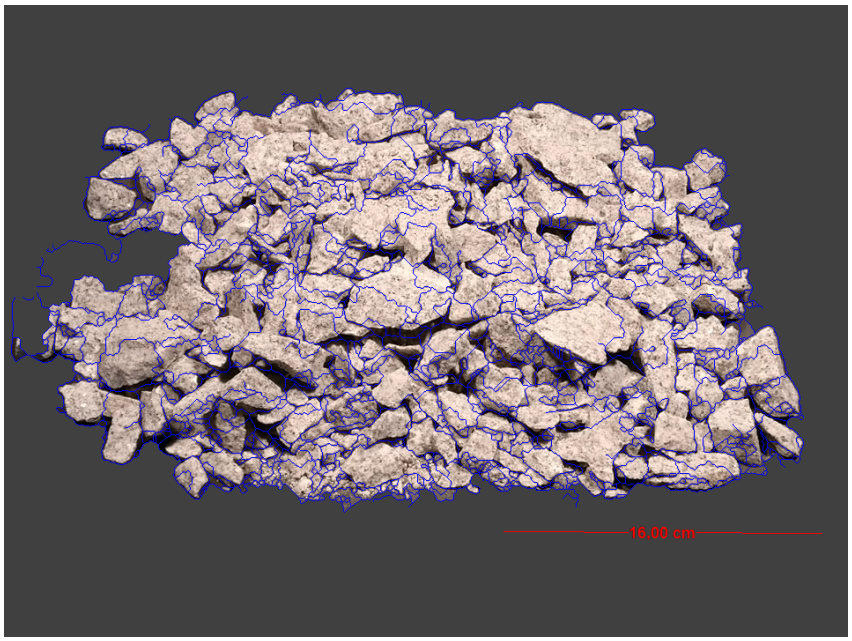

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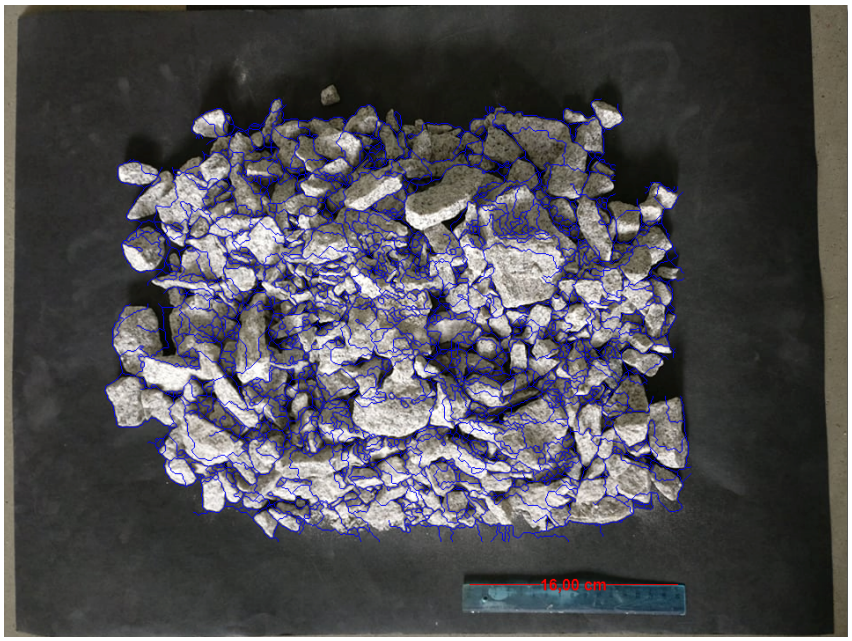

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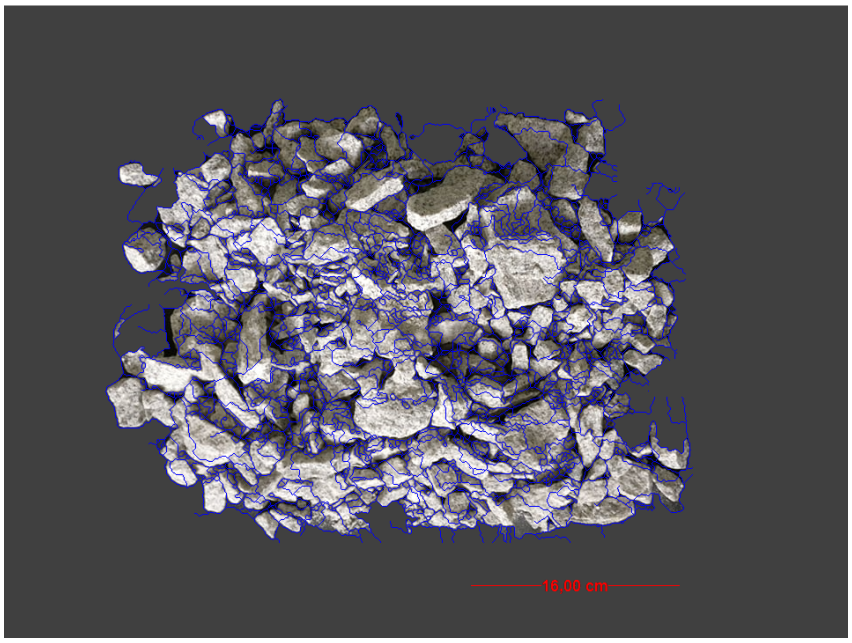

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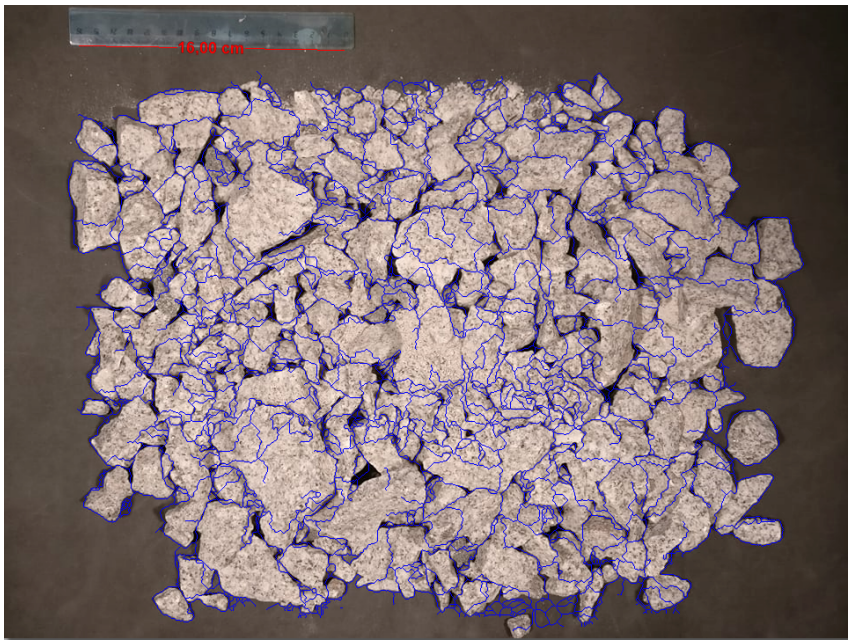

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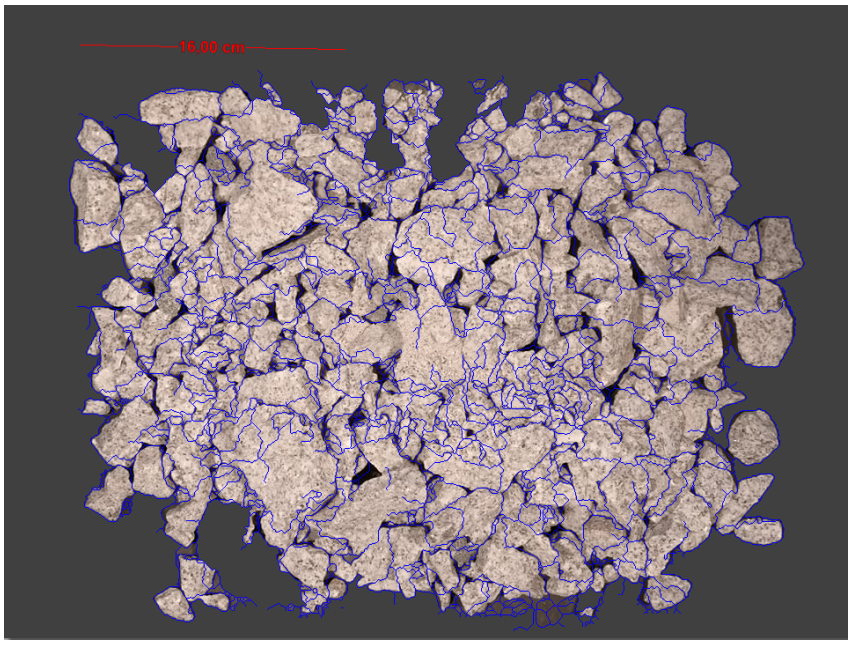

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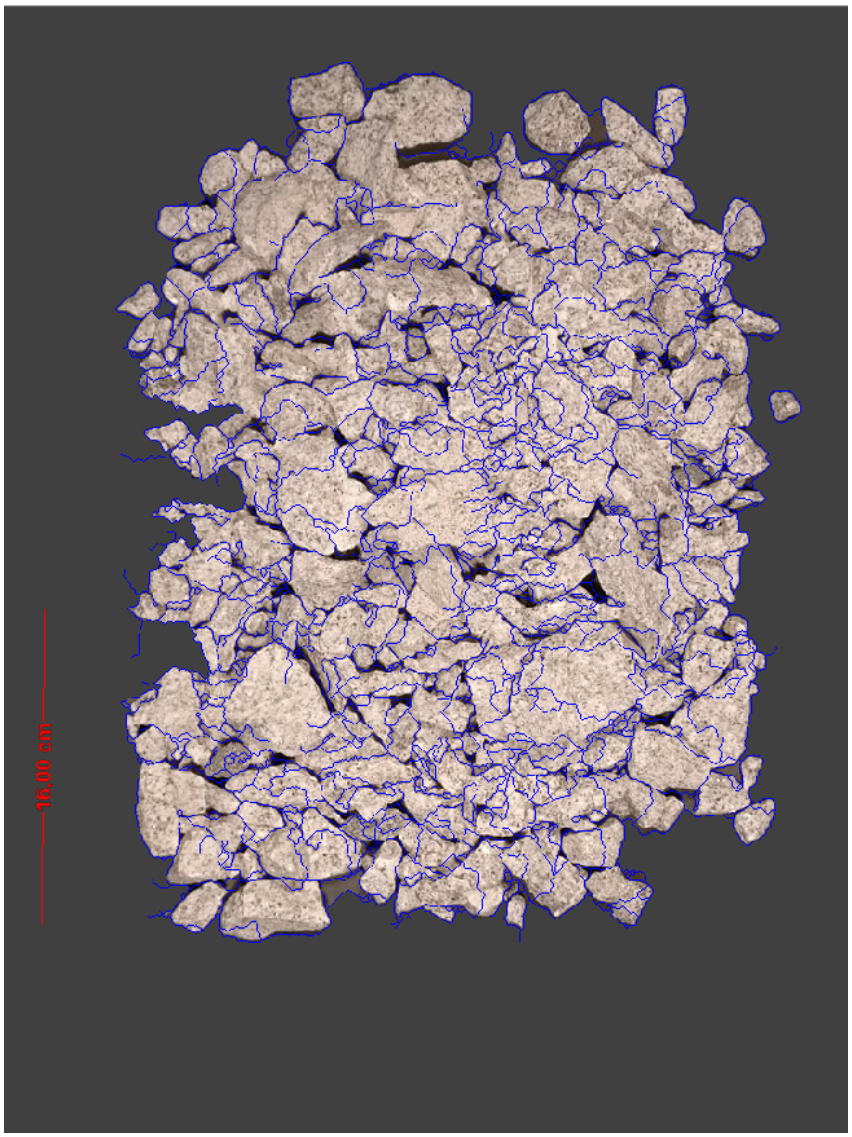

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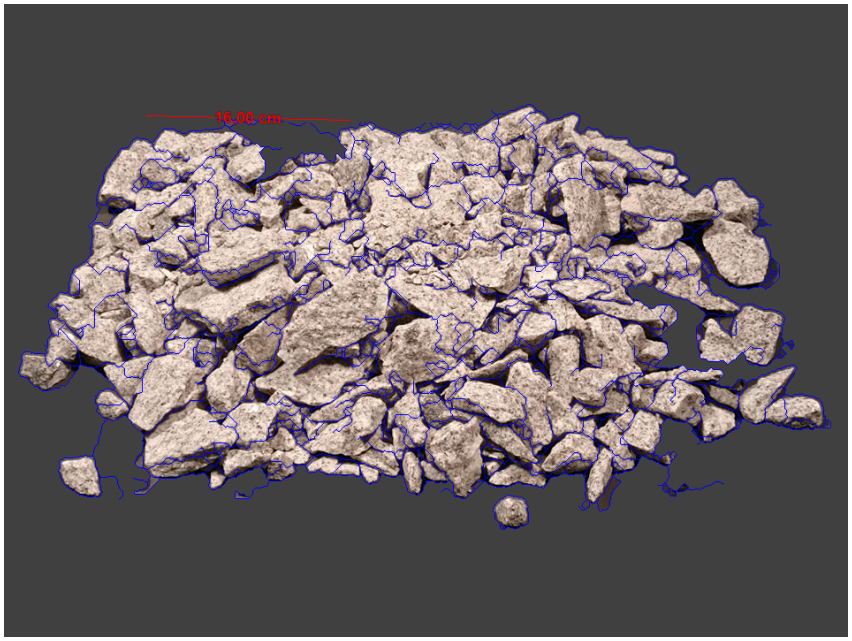

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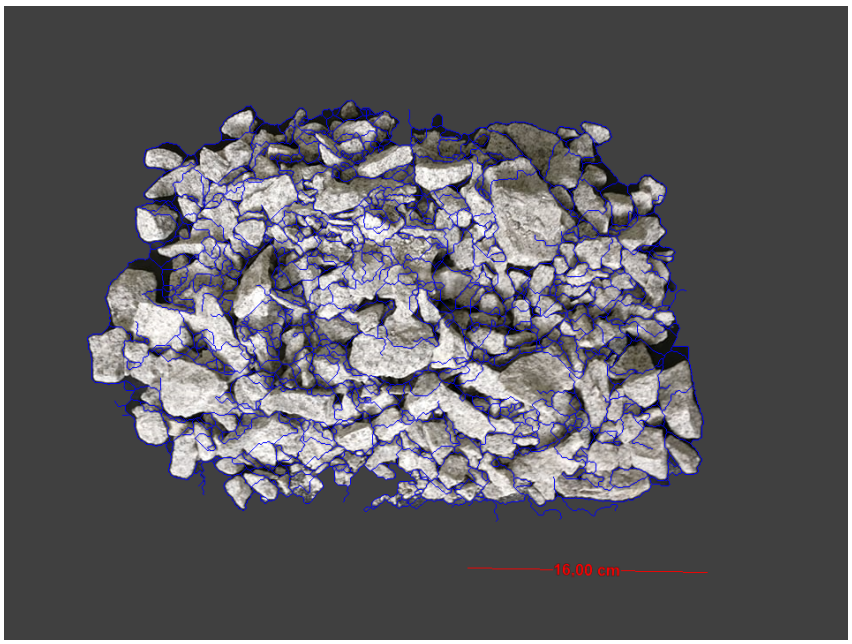

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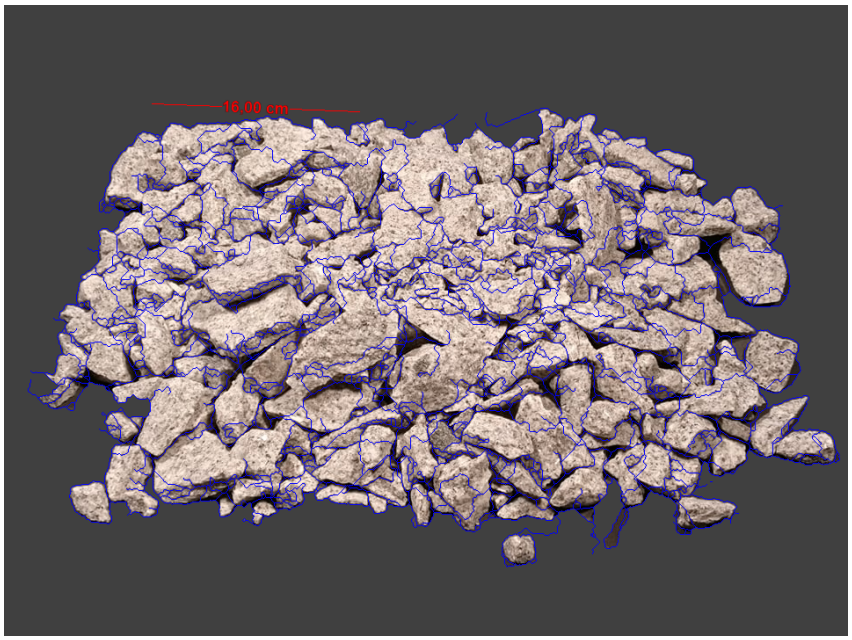

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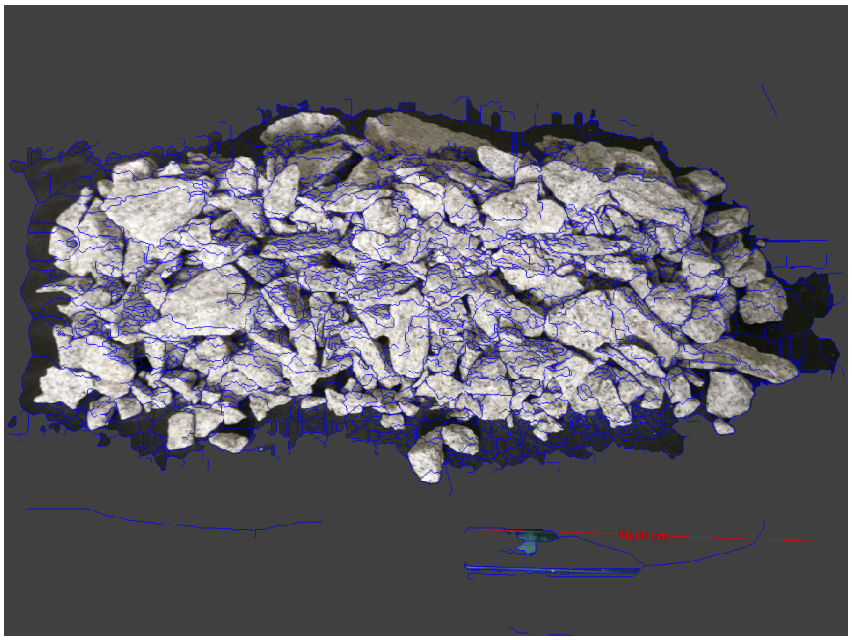

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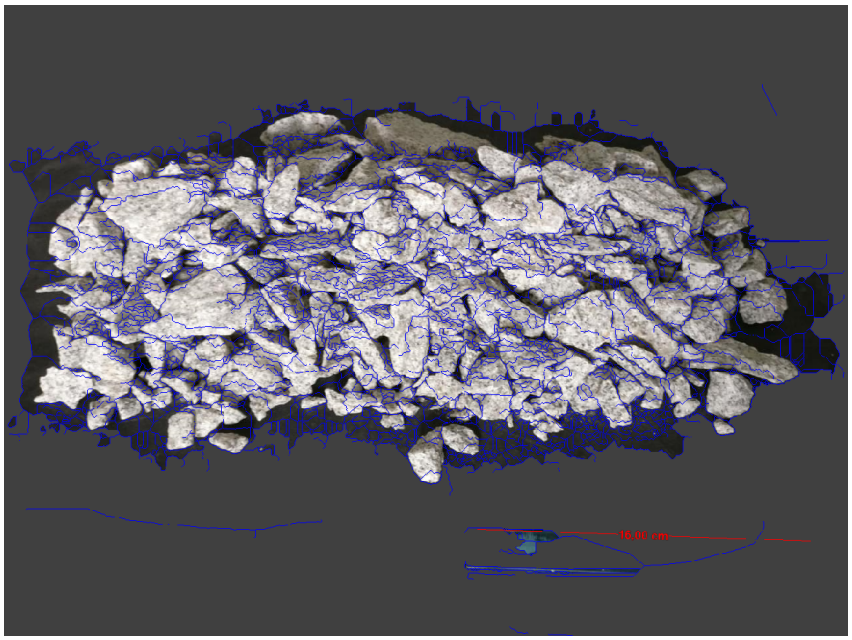

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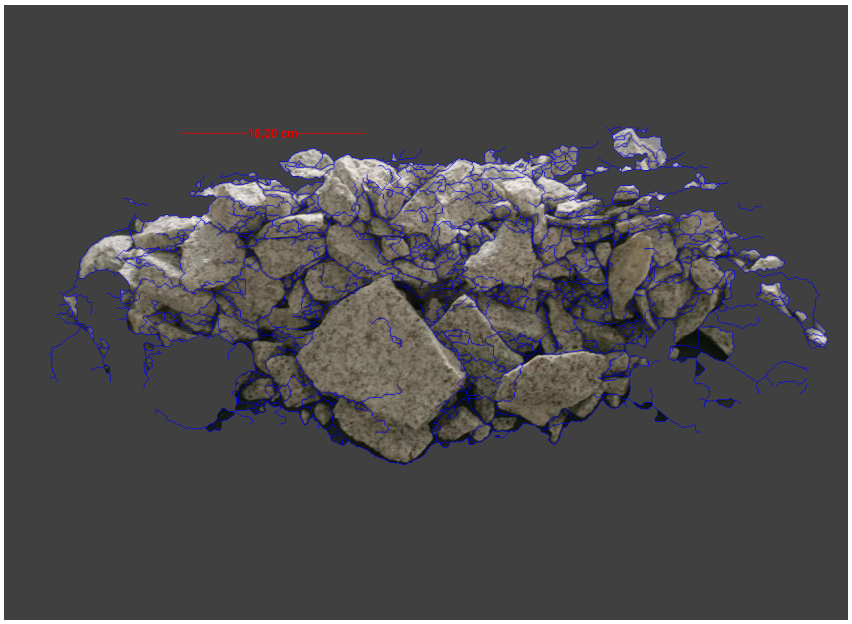

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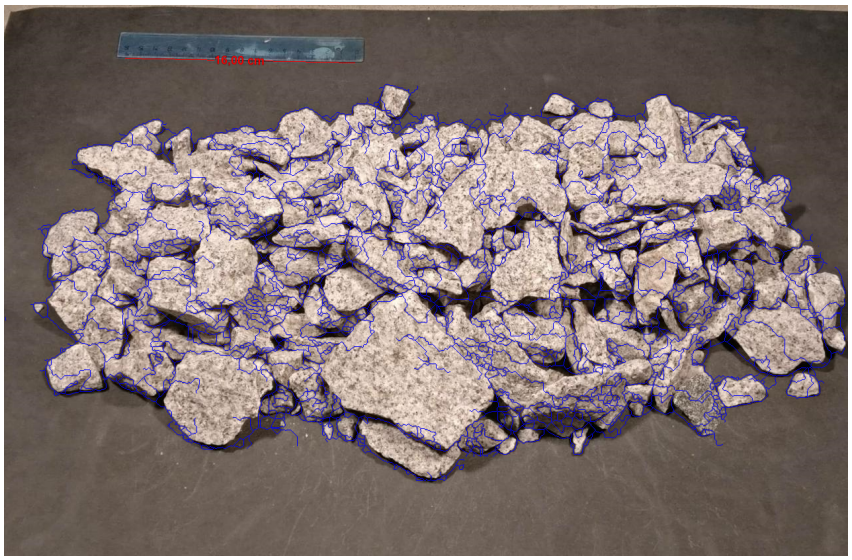

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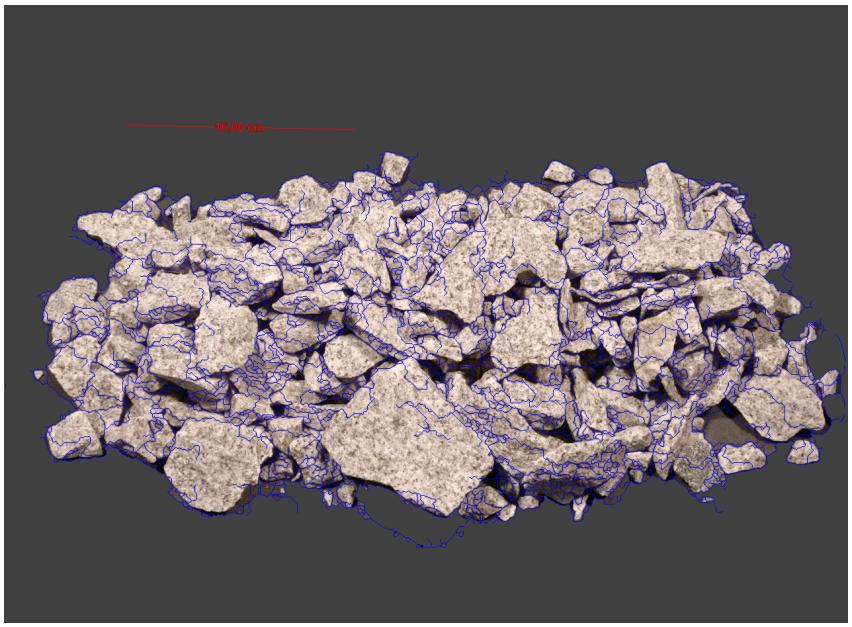

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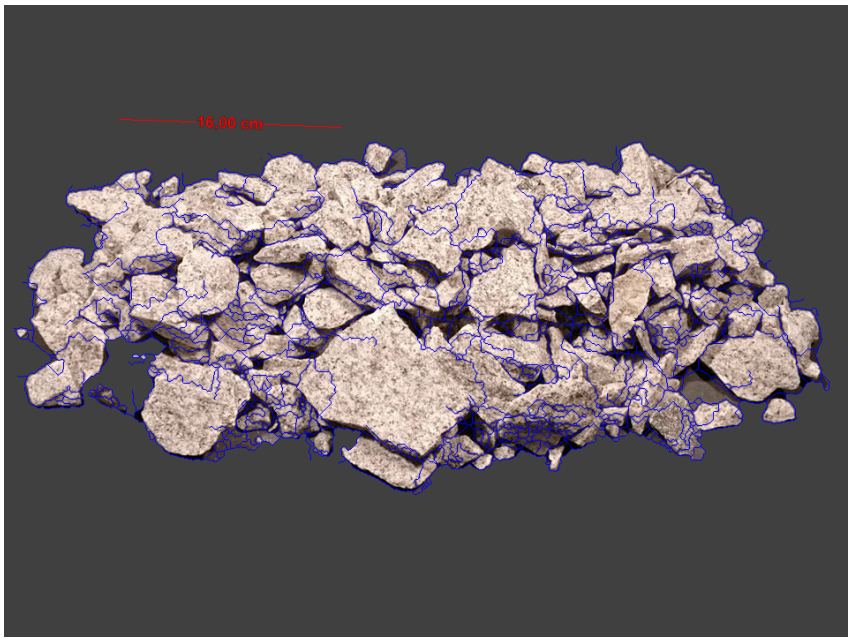

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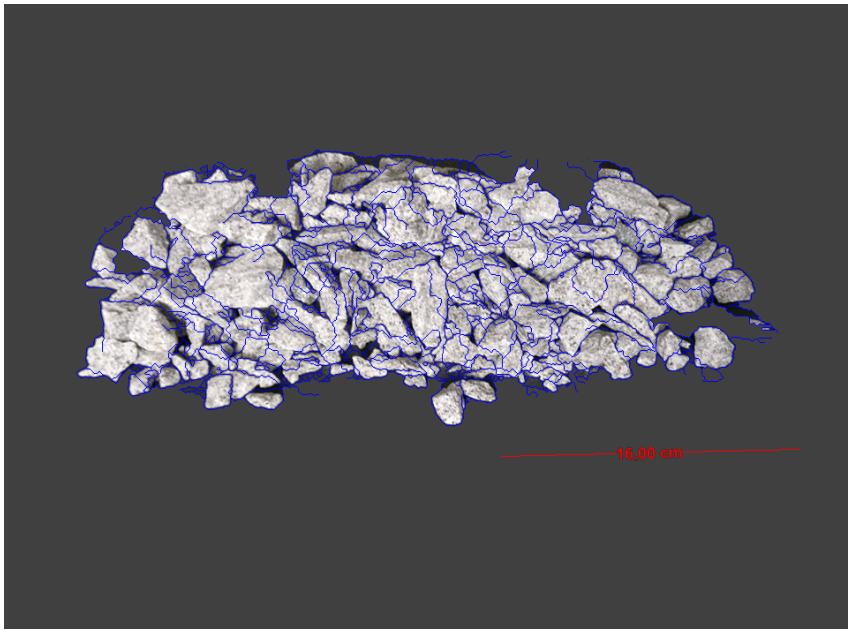

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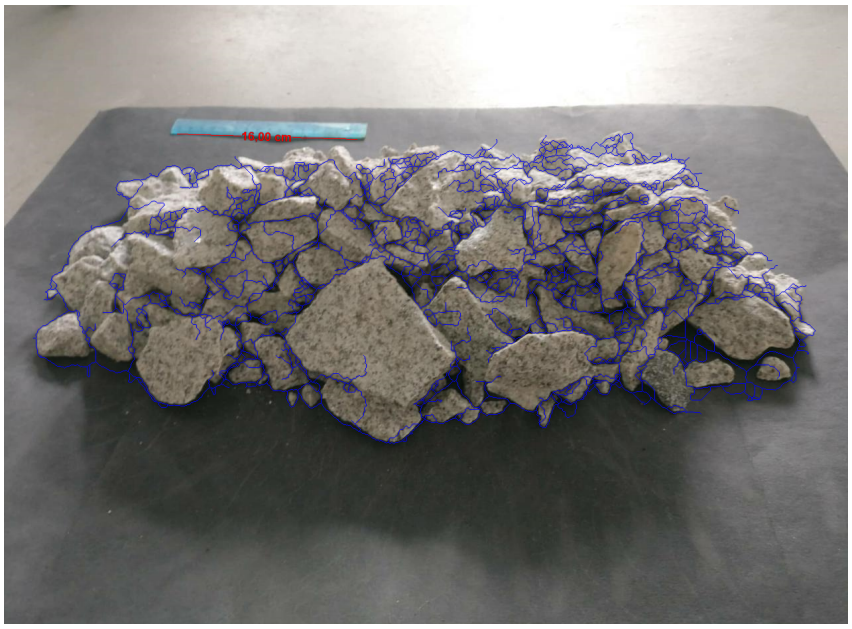

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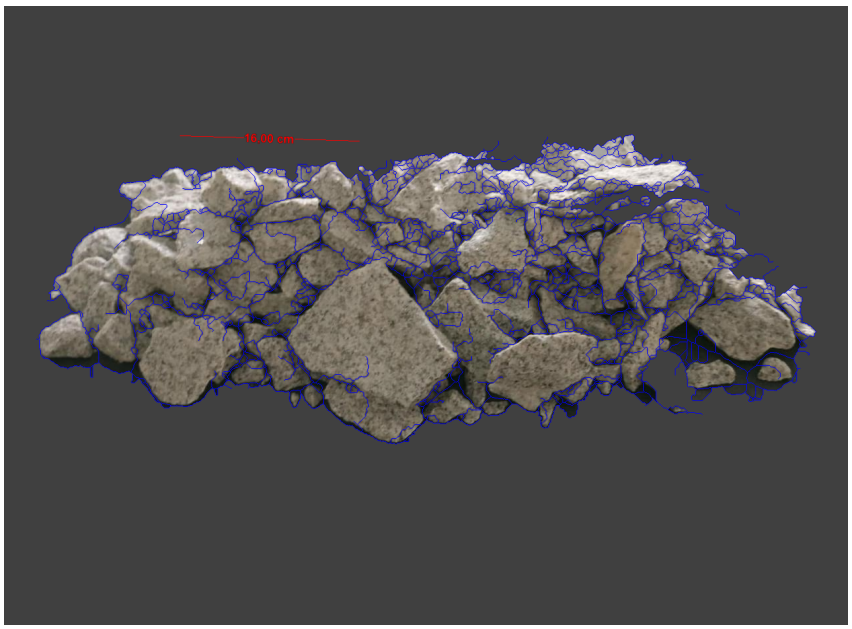

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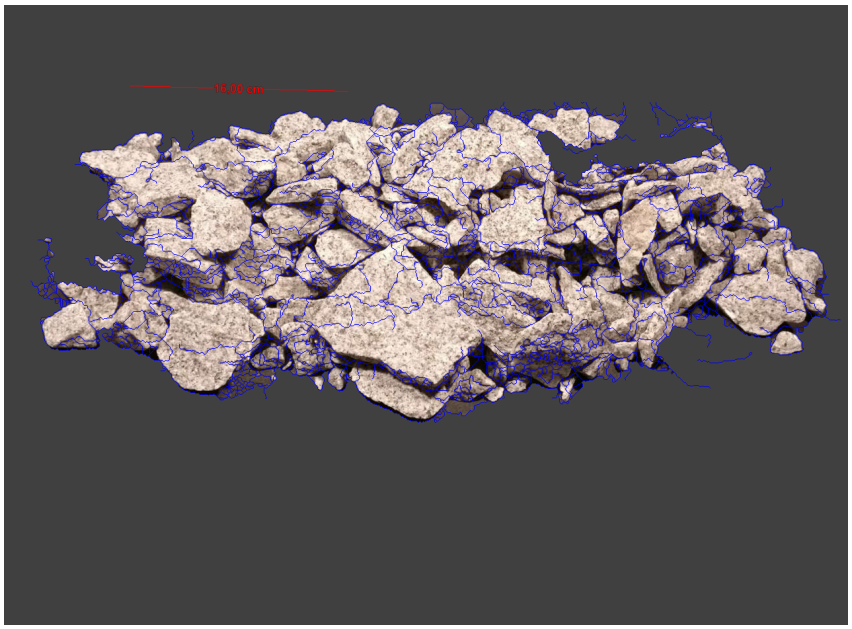

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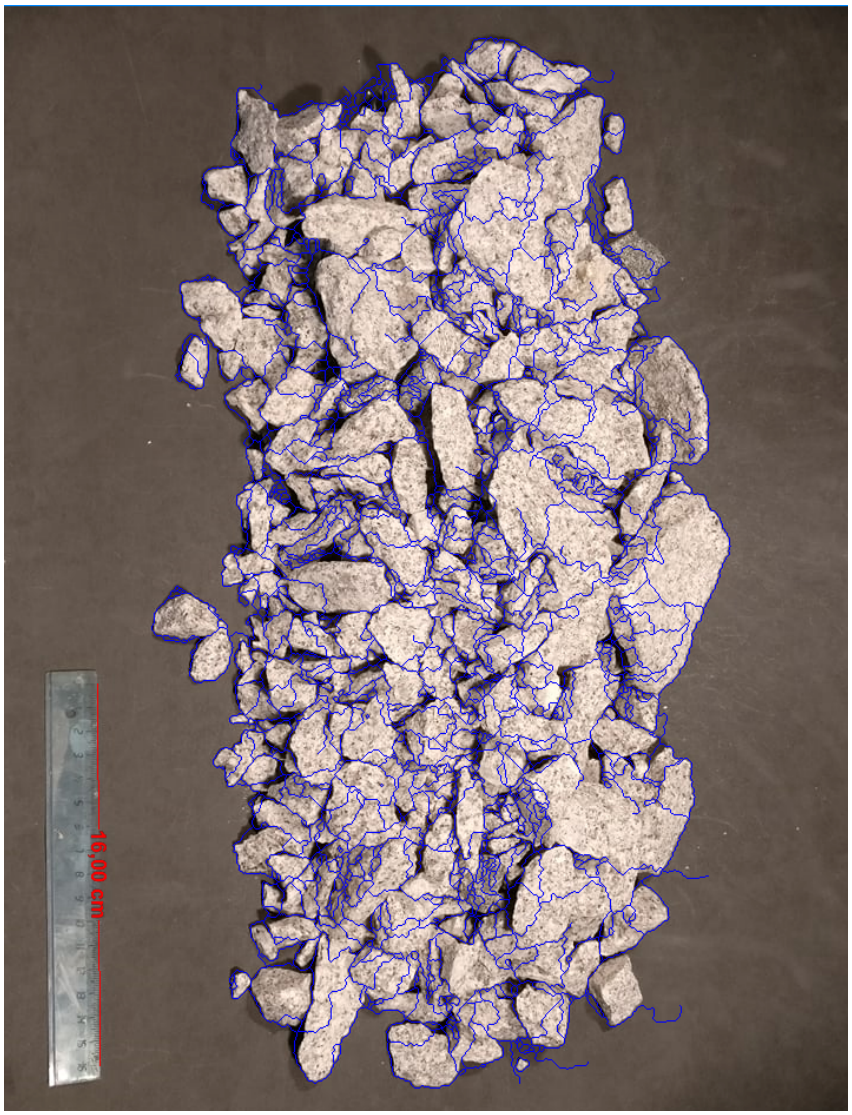

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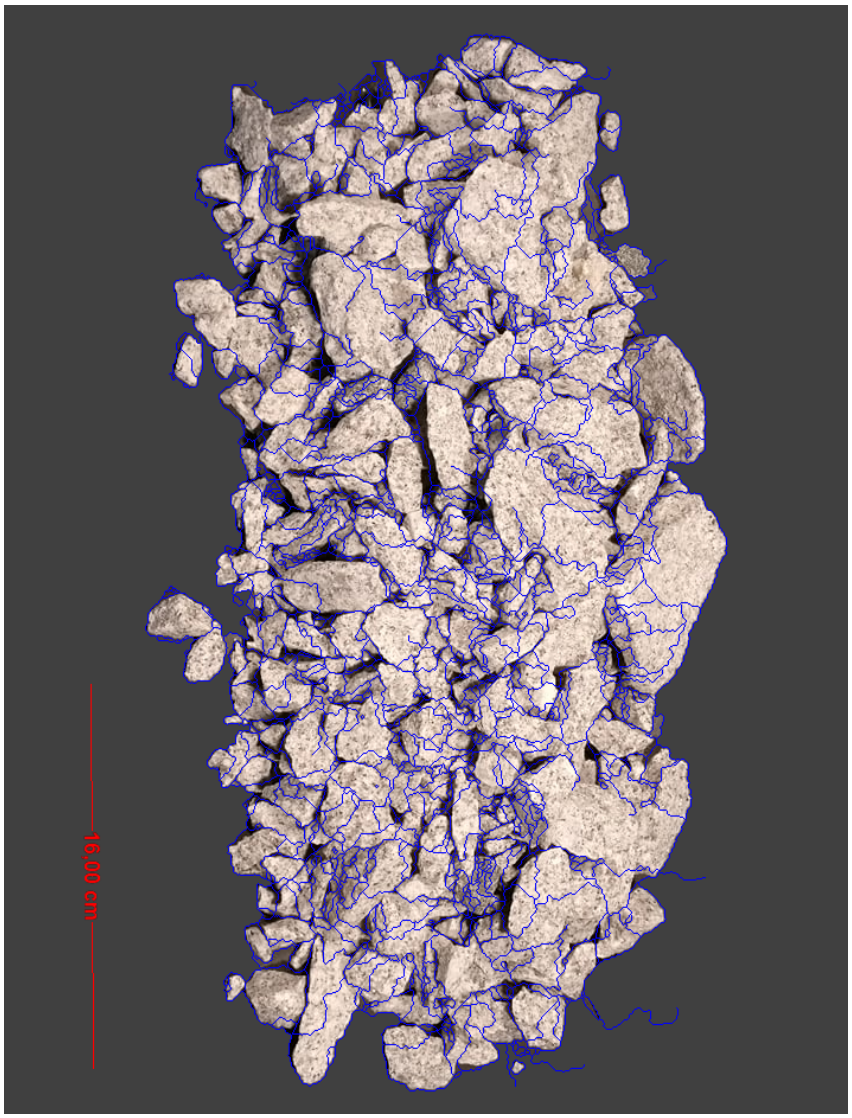

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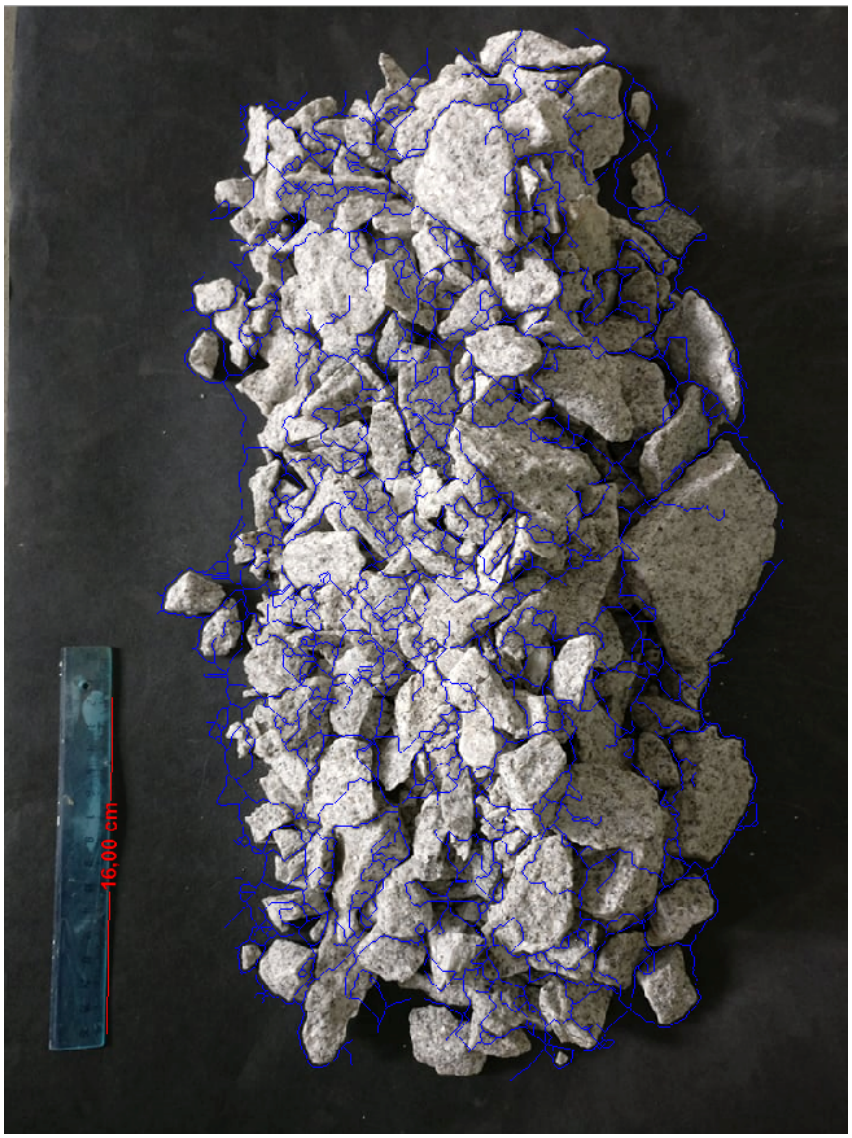

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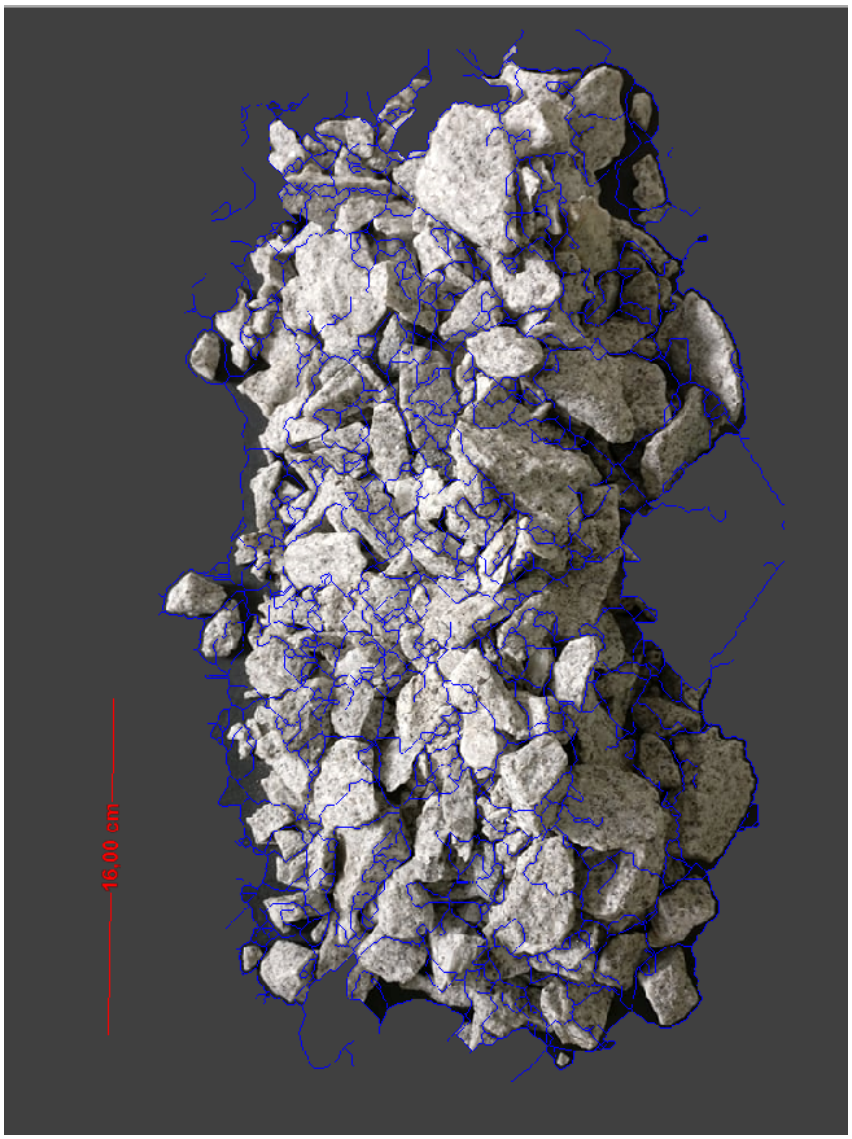

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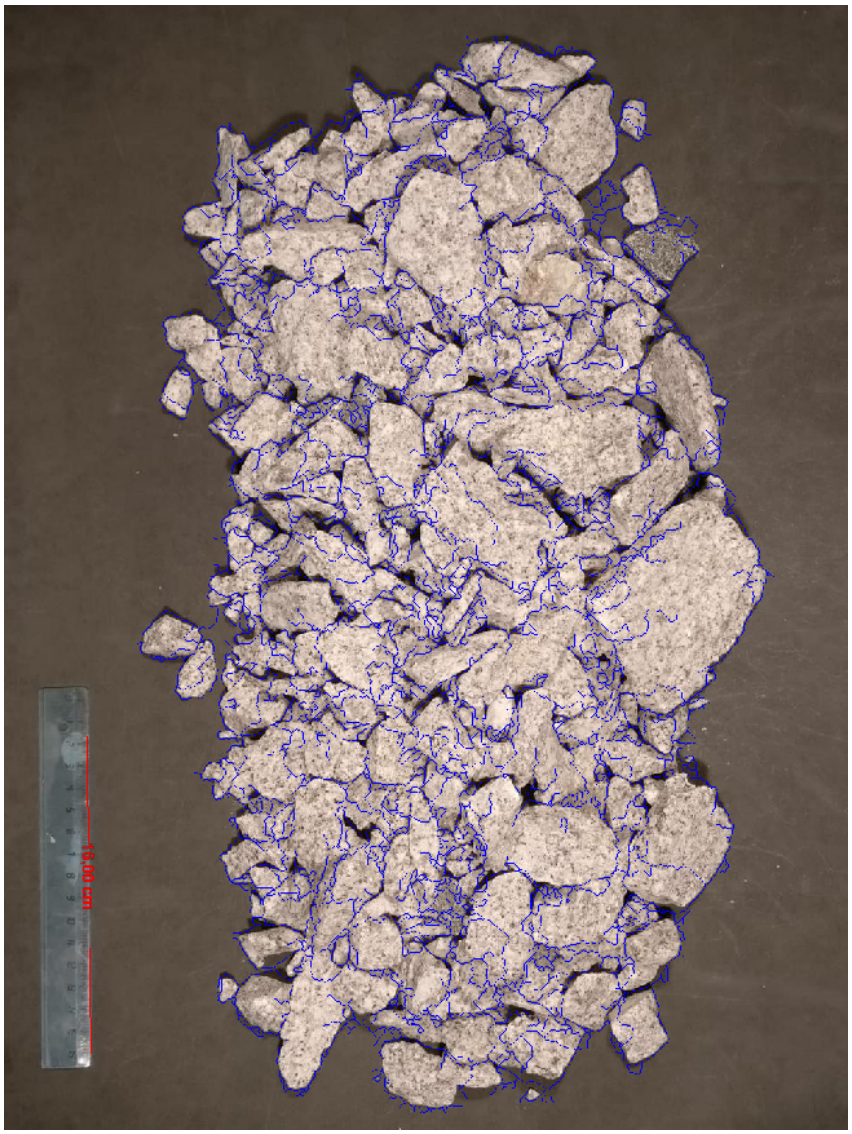

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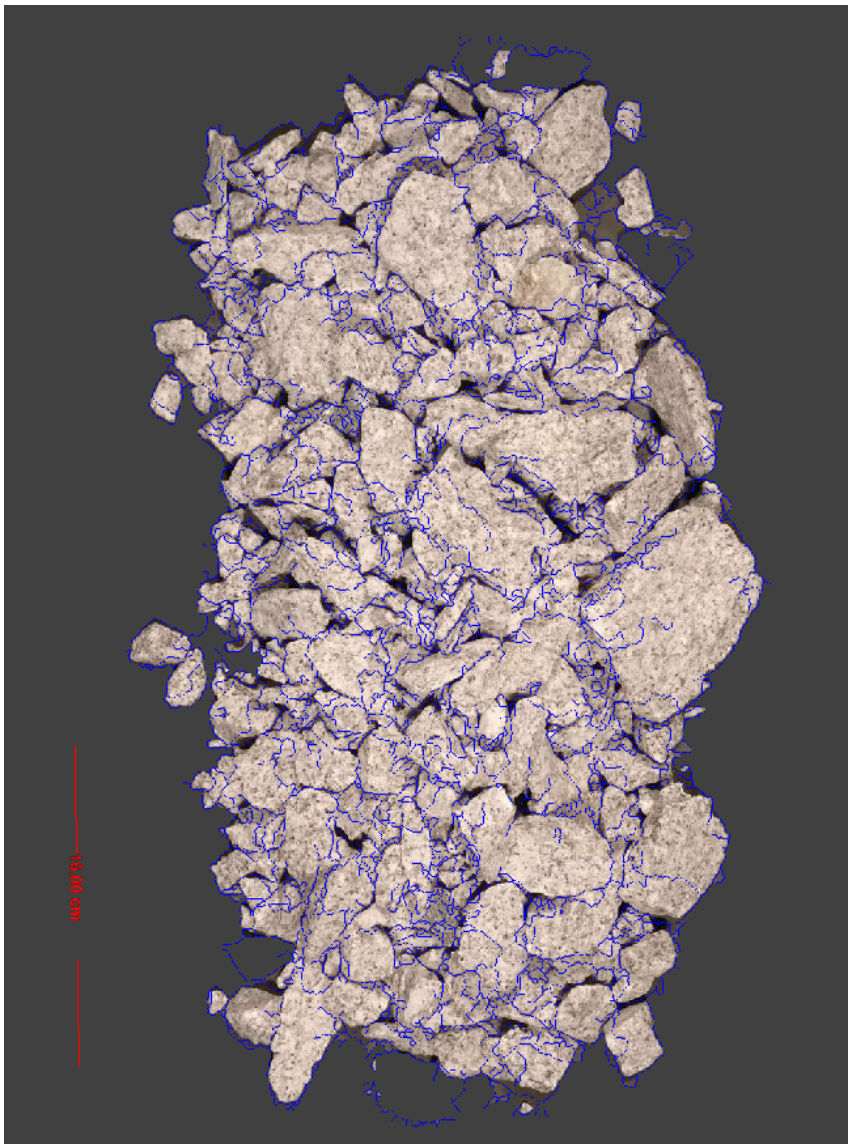

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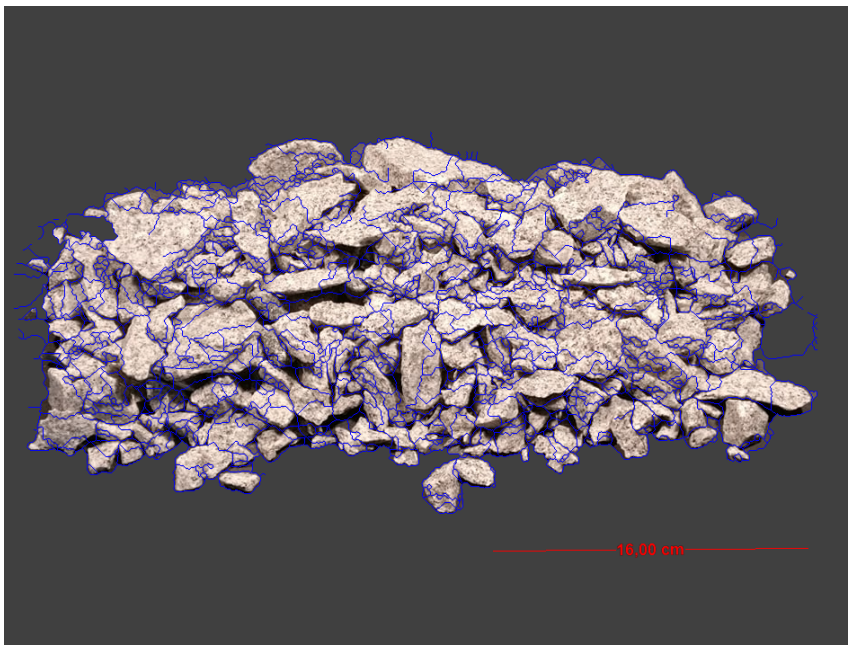

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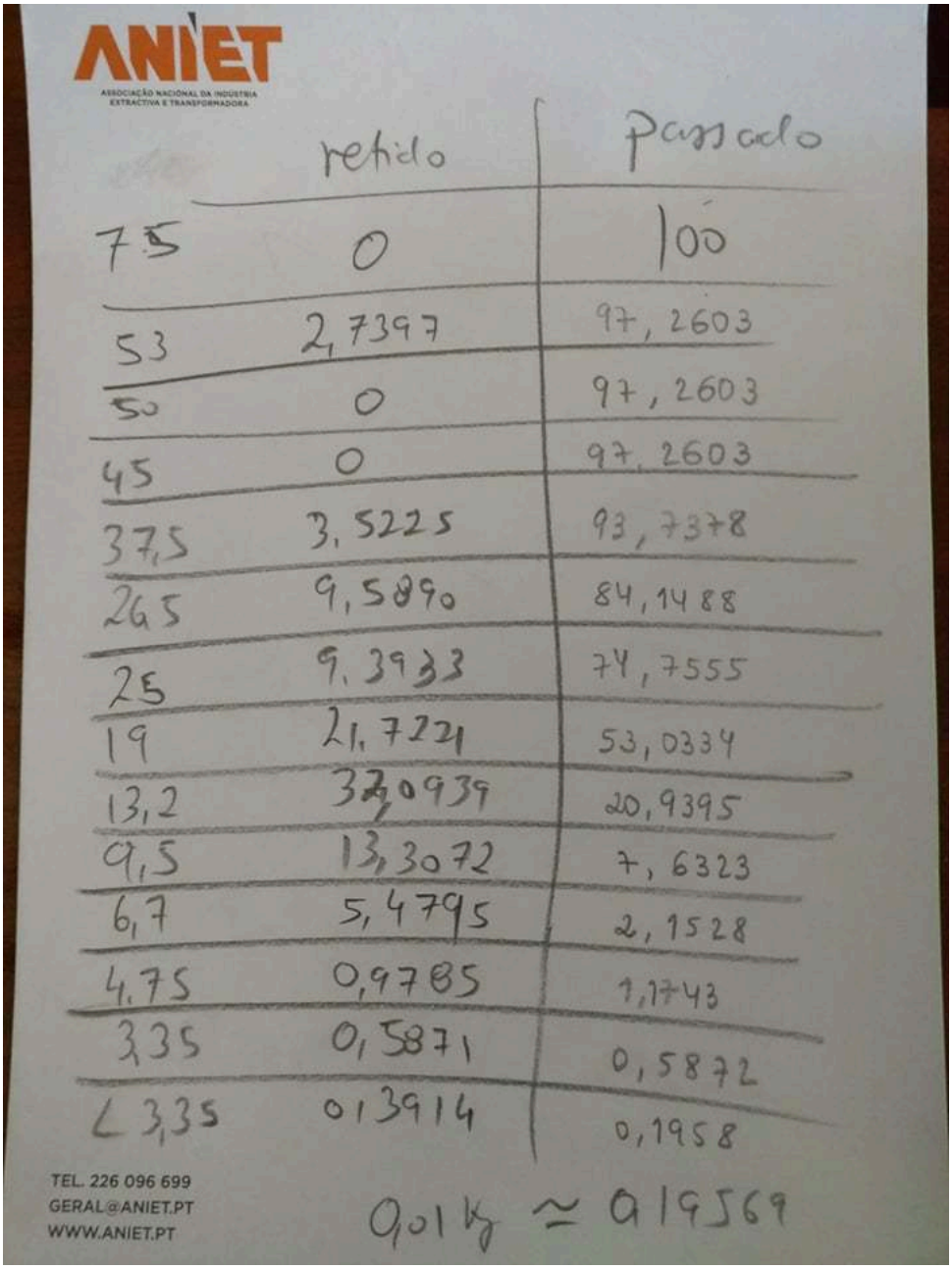
Handwritten notes



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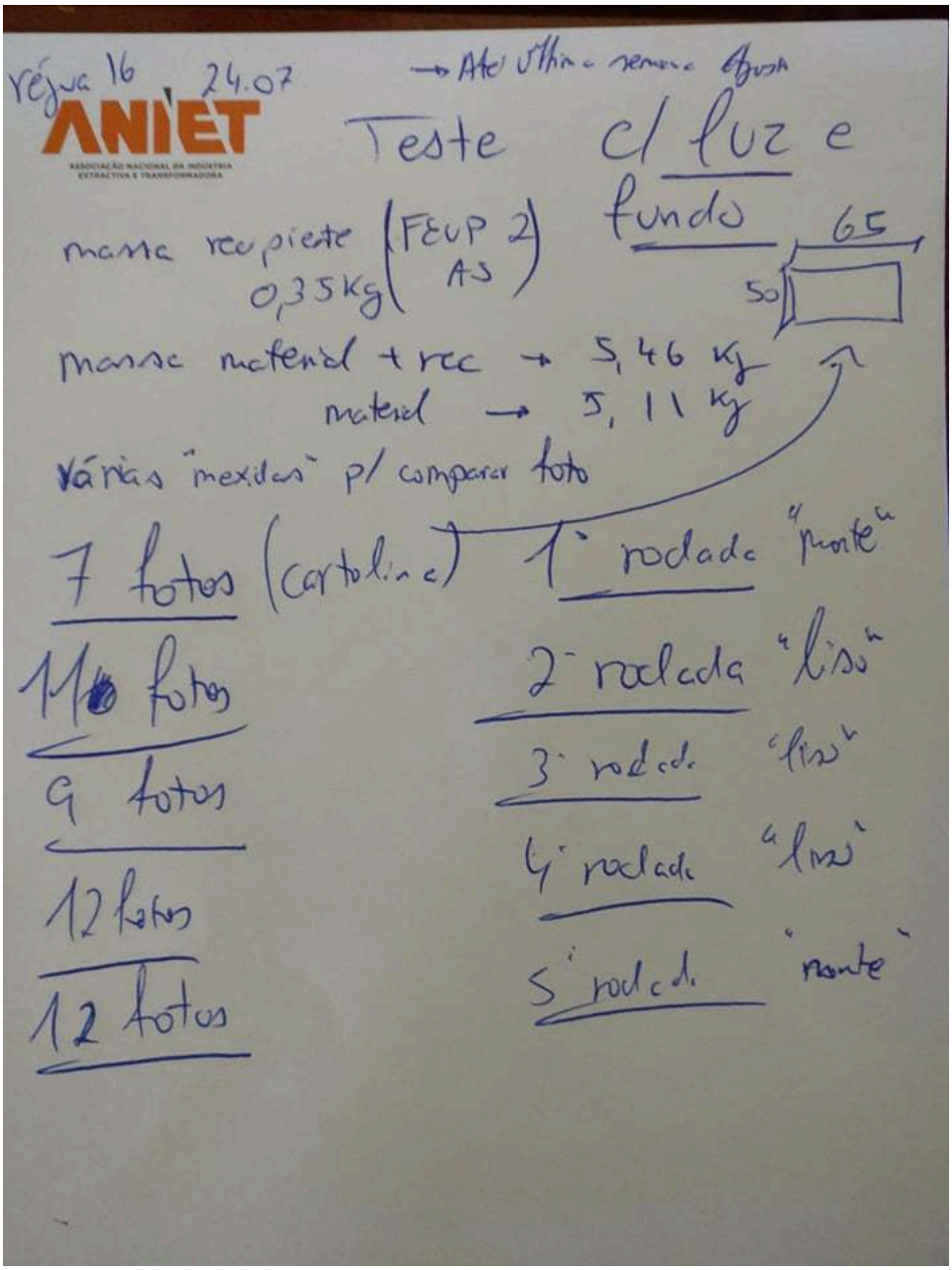
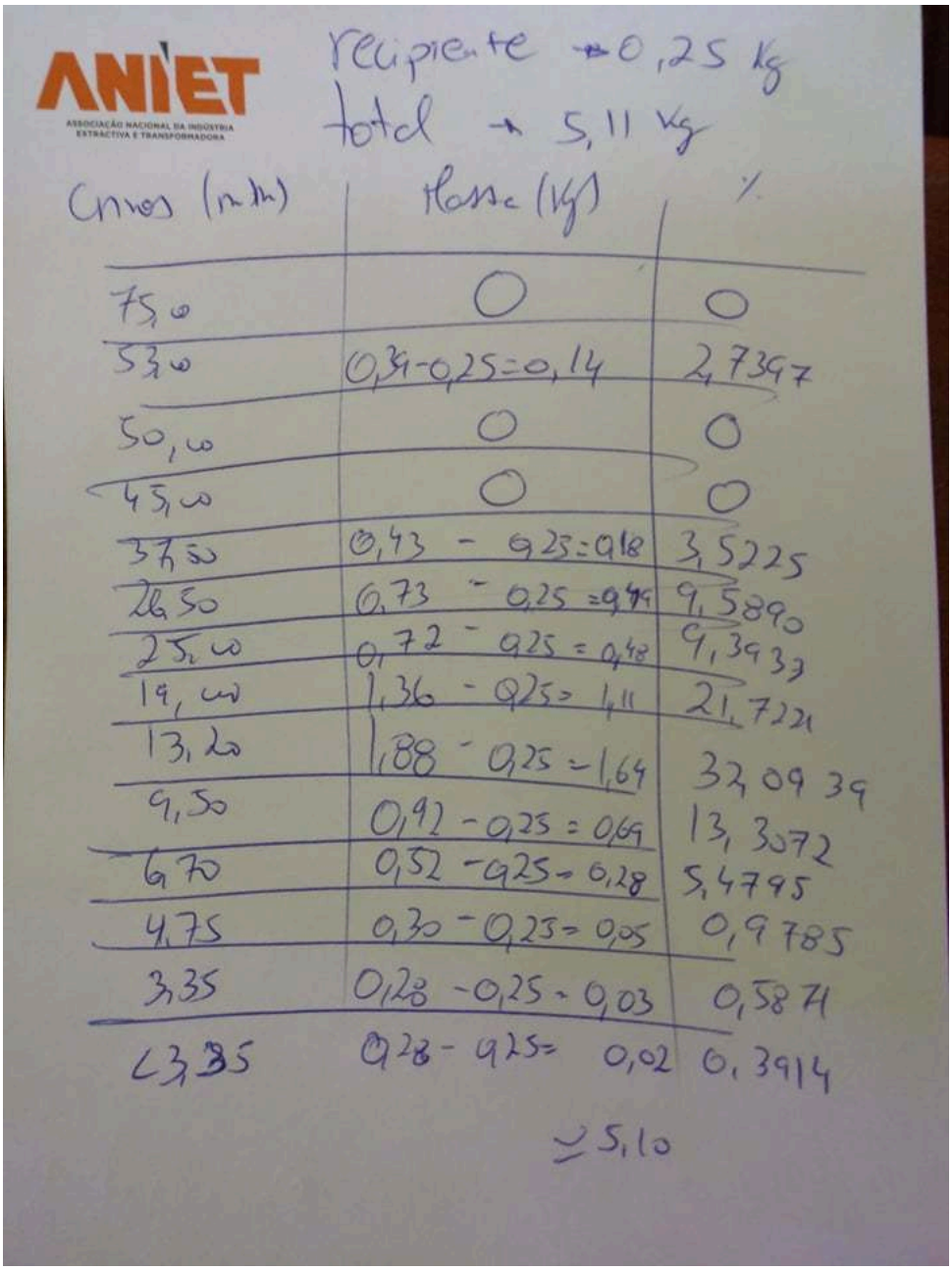


Handwritten notes 2



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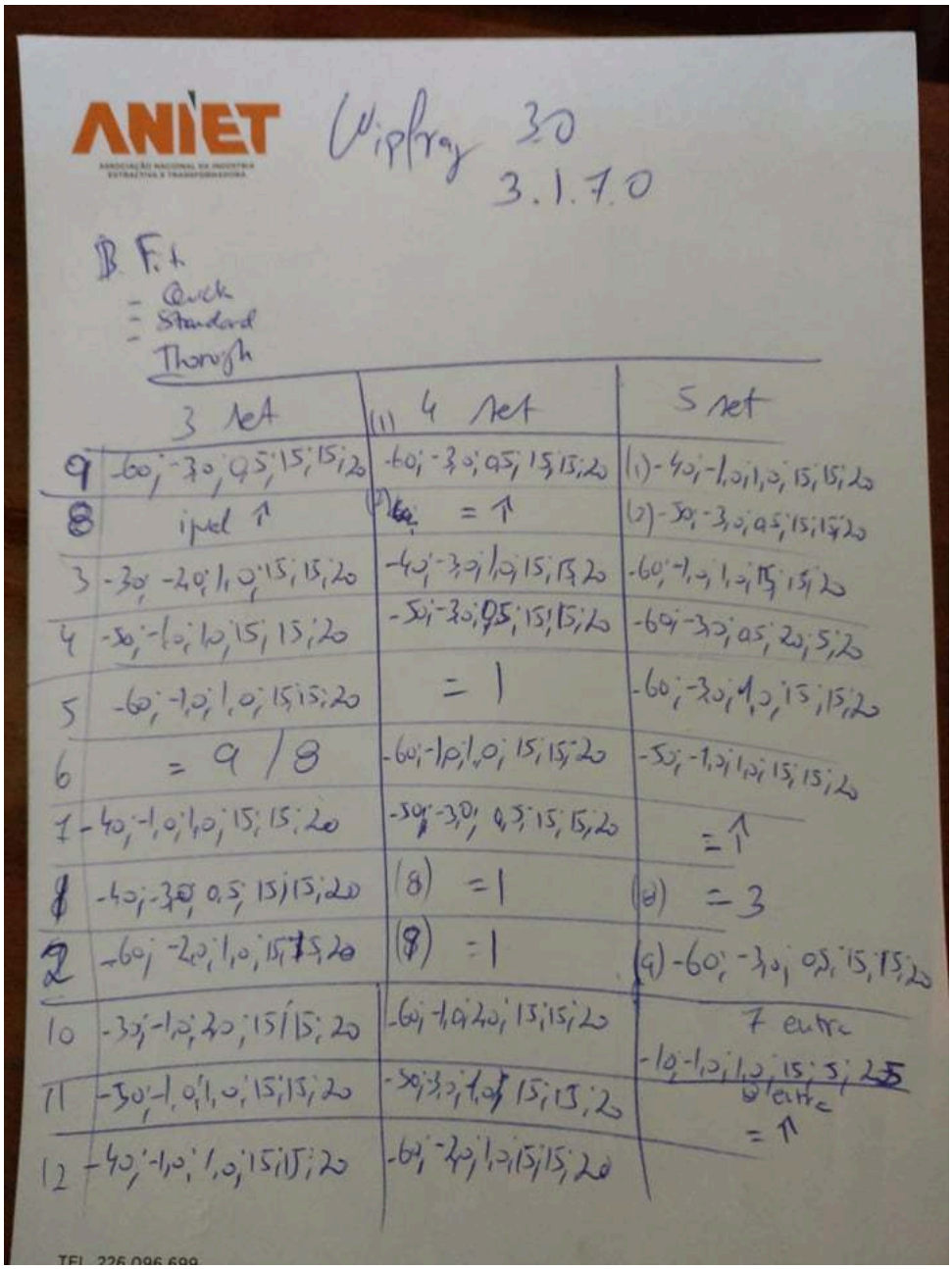
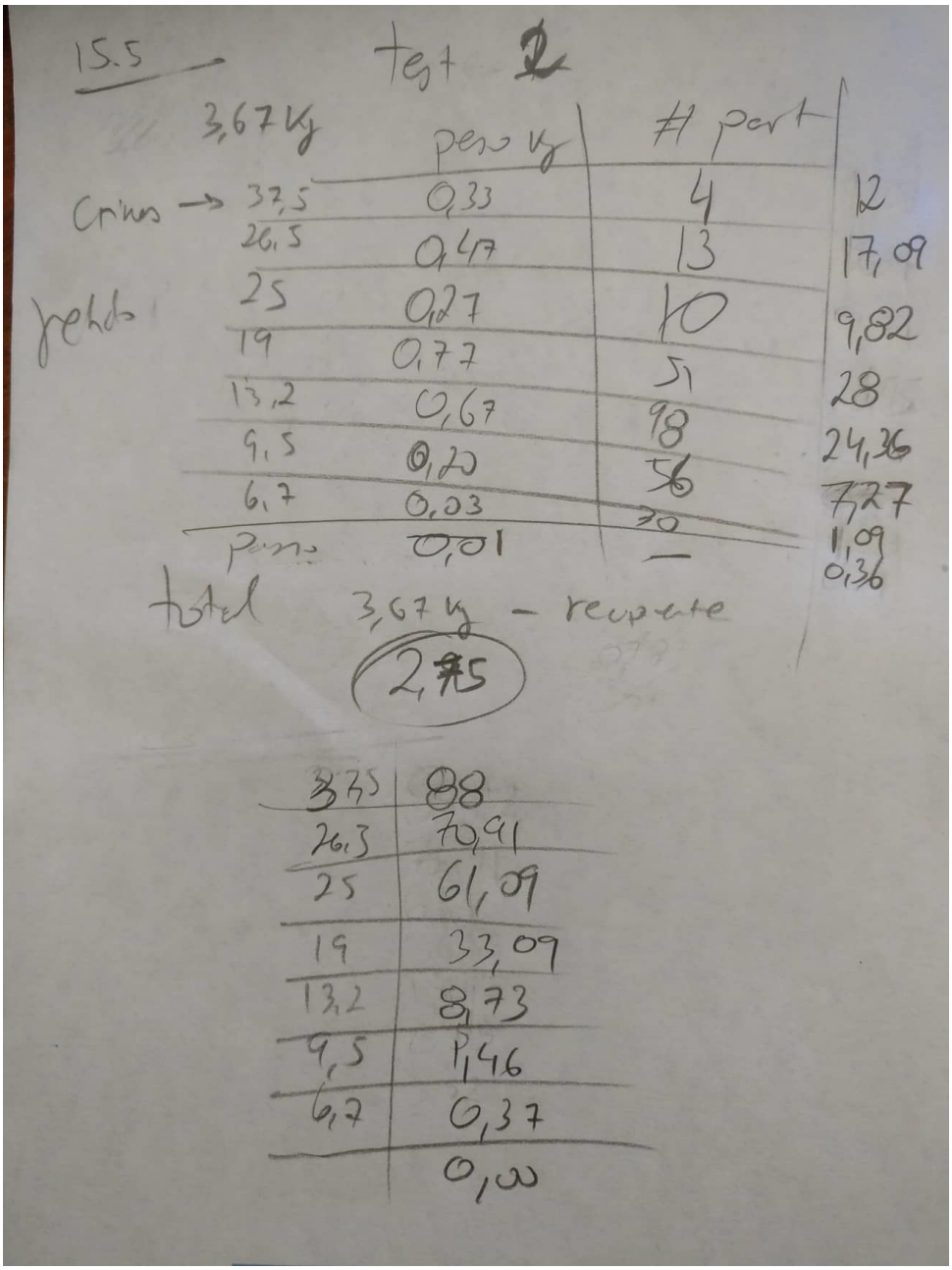
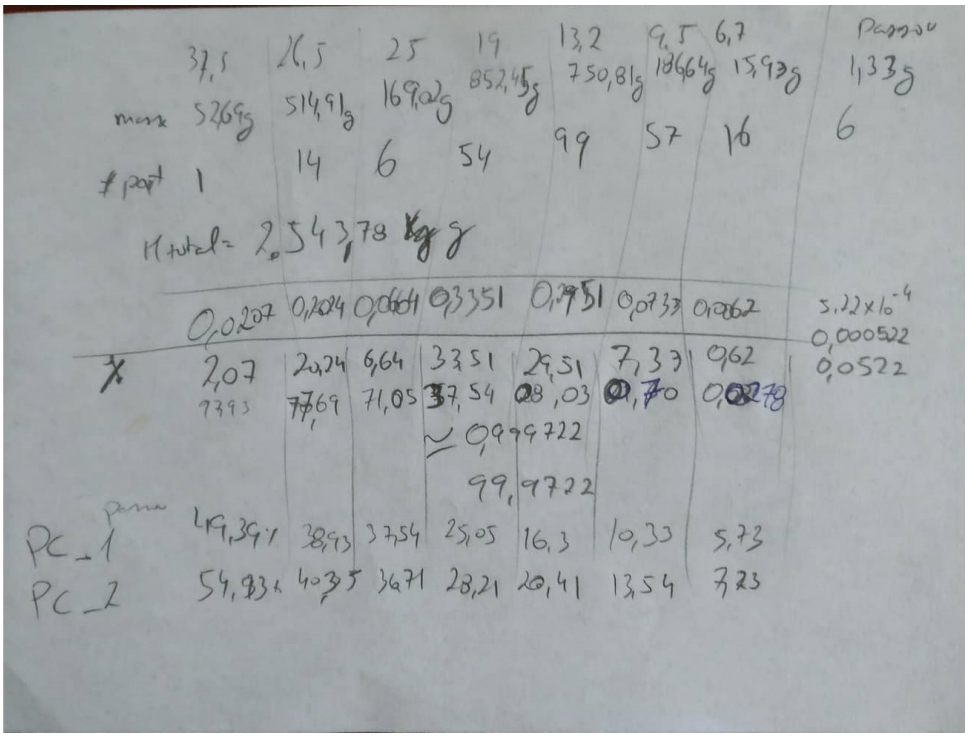


Handwritten notes 4



Handwritten notes 5



Handwritten notes 6